NAVPERS 93400A-2

FUNDAMENTALS OF ELECTRONICS

VOLUME 2

POWER SUPPLIES AND AMPLIFIERS

Bureau of Naval Personnel

PREFACE

This book is part of an nine-volume set entitled "Fundamentals of Electronics". The nine volumes include:

Volume 1a - NavPers 93400A-1a, Basic Electricity, Direct Current
Volume 1b - NavPers 93400A-1b, Basic Electricity, Alternating Current
Volume 2 - NavPers 93400A-2, Power Supplies and Amplifiers
Volume 3 - NavPers 93400-3, Transmitter Circuit Applications
Volume 4 - NavPers 93400-4, Receiver Circuit Applications
Volume 5 - NavPers 93400-5, Oscilloscope Circuit Applications
Volume 6 - NavPers 93400-6, Microwave Circuit Applications
Volume 7 - NavPers 93400-7, Electromagnetic Circuits and Devices
Volume 8 - NavPers 93400-8, Tables and Master Index

If you are becoming acquainted with electricity or electronics for the first time, study volumes one through seven in their numerical sequence. If you have a background equivalent to the information contained in volumes one and two, you are prepared to study the material contained in any of the remaining volumes. A master index for all volumes is included in volume eight. Volume eight also contains technical and mathematical tables that are useful in the study of the other volumes.

A question (or questions) follows each group of paragraphs. The questions are designed to determine if you understand the immediately preceding information. As you study, write out your answers to each question on a sheet of paper. If you have difficulty in phrasing an answer, restudy the applicable paragraphs. Do not advance to the next block of paragraphs until you are satisfied that you have written a correct answer.

When you have completed study of the text matter and written satisfactory answers to all questions on two facing pages of the book, compare your answers with those at the top of the next even-numbered page. If the answers match, you may continue your study with reasonable assurance that you have understood and can apply the material you have studied. Whenever your answers are incorrect, restudy the applicable material to determine why the book answer is correct and yours is not. If you make an honest effort to follow these instructions, you will have achieved the maximum learning benefits from each study assignment.

Follow the directions of your instructor in answering the review questions included at the end of each chapter.

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CHAPTER 15

POWER TRANSFORMERS

A transformer is a device that transfers electrical energy from one circuit to another by electromagnetic induction. The energy is always transferred without a change in frequency, but usually involves changes in voltage and current. A step-up transformer receives electrical energy at one voltage and delivers it at a higher voltage. Conversely, a step-down transformer receives electrical energy at one voltage and delivers it at a lower voltage. Transformers require little care and maintenance because of their simple, rugged, and durable construction.

REVIEW OF INDUCTION

15-1. Self-Inductance

Any change of current, either a rise or a fall, in a conductor causes a change of the magnetic flux around the conductor. Since a voltage is induced when magnetic flux lines cut across a conductor, this change in flux causes the generation of a voltage in the CONDUCTOR ITSELF as well as in nearby circuits. Therefore, in a coil consisting of a few turns of wire, a VARYING CURRENT produces magnetic flux around one turn which cuts across adjacent turns and induces a voltage in them. This induced voltage is always of opposite polarity to the applied voltage.

The sum of the voltages induced in all the turns of a coil is called a COUNTER EMF or a BACK EMF because it opposes a change in the current. Thus, if the current is increasing, the counter EMF tries to prevent the increase; if the current is decreasing, the counter EMF tries to prevent the decrease. The ability of a coil to generate a counter EMF is known as SELF INDUCTANCE of the coil. Therefore, the greater the opposition to a change in current, the greater is the inductance of a coil.

15-2. Mutual Inductance

When two coils are so placed in relation to each other that the magnetic lines of force produced by and encircling one coil link the turns of the other, the coils are said to be INDUCTIVELY COUPLED. If an ac voltage is applied to one coil, an ac voltage is induced in the second coil (Figure 15-1). This effect of linking two inductors is called MUTUAL INDUCTANCE (abbreviated M) and is measured in henrys.

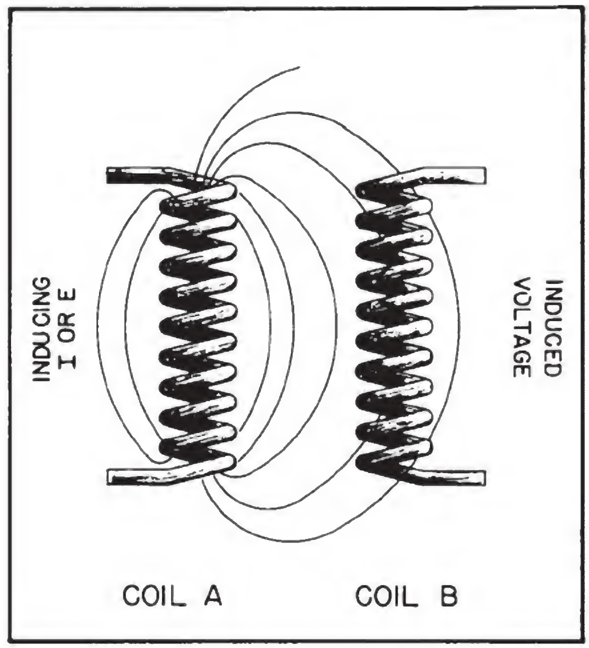

Figure 15-1 - Mutual inductance of two coils.

As in the case of self-inductance, the induced voltage is opposite in polarity to the exciting voltage. The amount of mutual inductance between two coils depends upon their size and shape, their relative positions, and the magnetic permeability of the medium between the two coils.

In Figure 15-1, not all of the lines of force set up by coil A cut the turns of coil B because the high reluctance of the magnetic circuit causes most of the flux lines to follow paths which do not link coil B. The extent to which two inductors are coupled is expressed by a COEFFICIENT OF COUPLING. This term is unity when all of the flux set up by one coil links the other, and it expresses the ratio of the mutual inductance actually present to the maximum value obtainable with unity coupling.

Q1. Compare the mutual inductance existing between two inductively coupled coils with an iron core, and with out an iron core.

TRANSFORMER CONSTRUCTION

15-3. Transformer Cores

A typical transformer consists of two coils of wire placed on some type of core material. In some cases the coils of wire may be wound on a cylindrical or a rectangular cardboard form. Since the space inside the windings contains only air, this type of transformer is called an AIR CORE TRANSFORMER. Air core transformers are used in circuits carrying radio frequency energy.

Transformers used for low frequency systems require a core of low reluctance magnetic material to concentrate and intensify the field about the windings. This type of transformer is called an IRON CORE TRANSFORMER. The power transformer used to supply the various voltages required by electronic equipment is of the iron core type.

Iron cores are usually manufactured in one of two shapes. Figure 15-2 shows the core construction of a CORE TYPE transformer. As shown, the core is fabricated from a number of thin silicon steel stampings called LAMINATIONS. These laminations are covered with an insulating varnish and then pressed together to form the core.

The most popular and efficient type of transformer core is called a SHELL TYPE CORE. The construction of this type of core is illustrated in Figure 15-3. As shown, the core consists of a number of laminations. Each layer of the core consists of an E and an I shaped section of metal which are butted together to form the lamination. The laminations are insulated from each other and then pressed together to form the core.

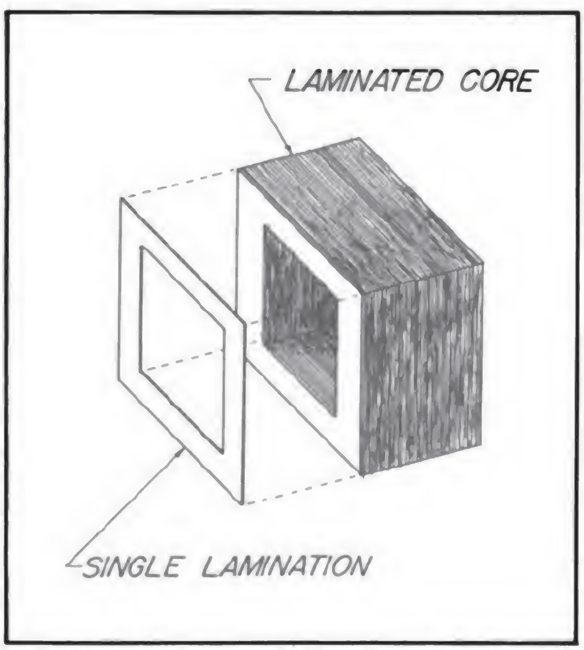

Figure 15-2 - Core type construction.

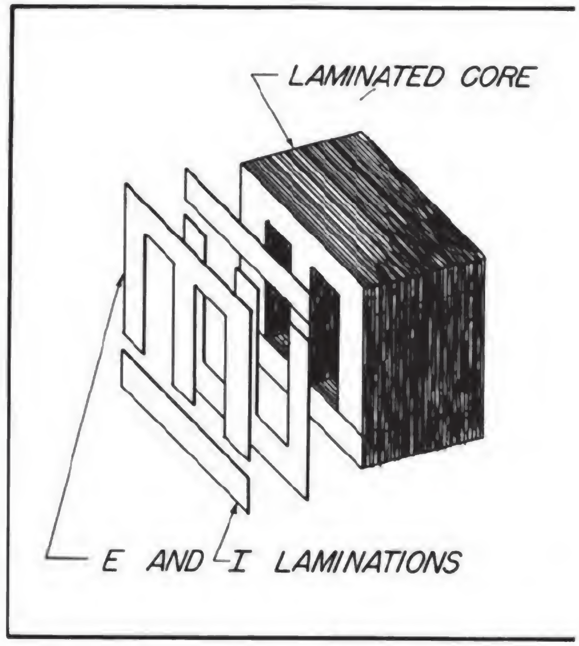

Figure 15-3 - Construction of shell type core.

Q2. Compare the coefficient of coupling of a radio frequency transformer to the coefficient of coupling of a power transformer.

15-4. Transformer Windings

In its most basic form a power transformer consists of two coils called WINDINGS which are placed on one of the two types of cores discussed above. To place the transformer into operation a source of alternating current is connected to one of the windings and a load device is connected to the other. The winding that is connected to the source is called the PRIMARY WINDING. The winding that supplies energy to the load is called the SECONDARY WINDING.

Figure 15-4 shows an exploded view of a shell type transformer. In constructing the transformer, the primary winding is wound in layers on a rectangular cardboard form. In the transformer illustrated, the primary consists of many turns of relatively small wire. The wire used for the winding is coated with varnish so that each turn of the winding is insulated

from every other turn. In transformers designed for high voltage applications, paper is placed between the layers of a given winding to provide additional insulation.

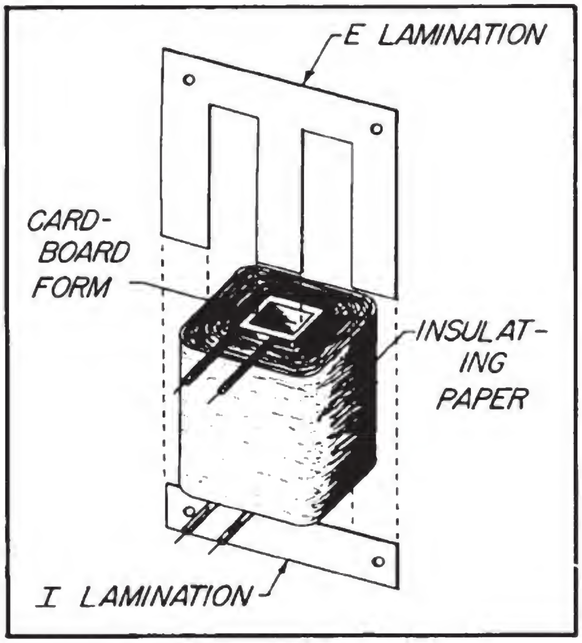

Figure 15-4 - Exploded view of transformer.

When the winding of the primary is complete, the winding is wrapped in insulating paper or cloth. The secondary winding is then wound on top of the primary winding. After the secondary winding is complete, it too is covered with insulating paper, and the E and I sections of the iron core are assembled on the windings. (Figure 15-4)

When finished the transformer appears as shown in the cut-away view of Figure 15-5. Notice that the shell type core completely surrounds the windings providing the maximum possible magnetic coupling between the windings. In some transformers, a metal case is placed over the entire transformer to protect the windings from mechanical damage. The leads may be brought out through a hole in the case, or terminals may be provided on the case to make connections to the windings.

In most cases a power transformer will contain more than one secondary winding, and in rare cases may contain more than one primary. Frequently, additional connections are made to a transformer winding at points other than the ends of the winding. These additional connections are called TAPS. When the tap is placed in the center of a winding it is called a CENTER TAP. The schematic symbols for transformers are shown in Figure 15-6.

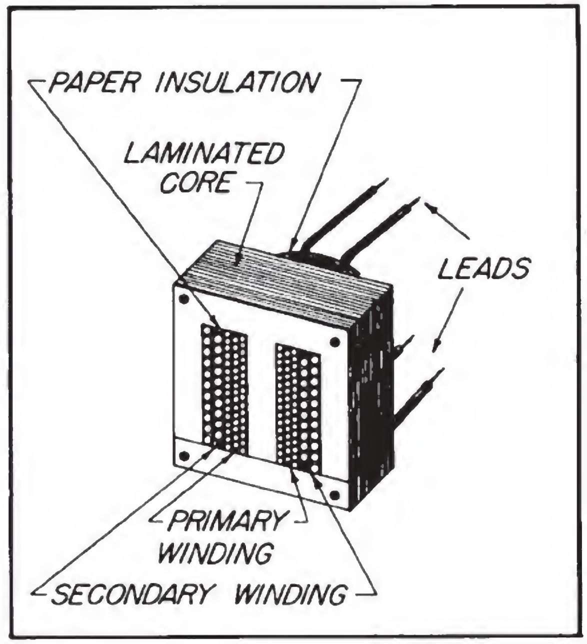

Figure 15-5 - Cut-away view of two winding transformer.

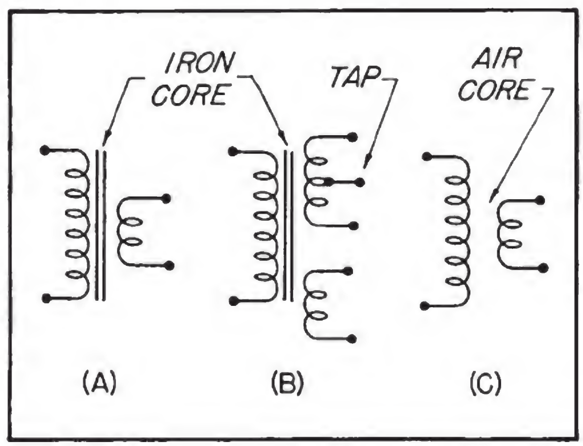

Figure 15-6 - Schematic symbols for various types of transformers.

Q3. What factors determine which winding of a transformer is called the primary?

TRANSFORMER THEORY

15-5. Primary Conditions With No Load

The theory of transformer action will be analyzed using the simplified diagram of a transformer illustrated in Figure 15-7.

A1. The mutual inductance would be much greater with the iron core since its low reluctance would increase and concentrate the flux.

A2. The power transformer would have a much higher coefficient of coupling due to the use of an iron core.

A3. The connections to the circuit. The winding connected to the source is always called the primary.

This transformer consists of a 60 turn primary and a single turn secondary winding. Notice that both windings are wound in the same direction (clockwise from top to bottom). To simplify the diagram, the iron core has been omitted from the drawing. Throughout the discussion, however, it will be assumed that the transformer has a standard shell type core.

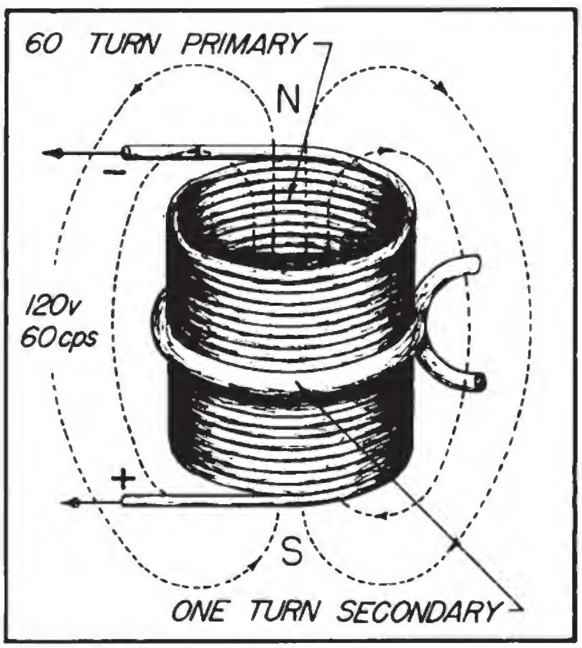

Figure 15-7 - Simple transformer (iron core not shown).

If 120 volts at 60 cycles per second are applied to the primary, and no connection is made to secondary, the primary appears as a simple iron core inductance connected across the 120 volt ac line.

Since the primary is essentially an inductance, the current flowing in the primary will depend mainly on the amount of applied voltage, the frequency of the applied voltage, and the inductance of the primary winding.

If the action of the transformer is analyzed at an instant of time when the source current is flowing into the top lead of the primary and out of the bottom lead, the left-hand rule indicates the top of the coil to have north magnetic polarity. As the field about the coil builds up, the expanding lines of force generated by the primary cut each turn of the primary coil and induce a counter EMF into the primary (self-induction). This self-induced EMF is opposite in polarity to the applied voltage, and nearly equal to it. As a result, the primary current is small and lags the applied voltage by almost 90°. This small current which flows when the secondary is open is called EXCITING CURRENT.

The exciting current flowing in the primary of a transformer can be thought of as consisting of two components. One of these components establishes the flux in the transformer core and causes no dissipation of power. This current is called the MAGNETIZING CURRENT, (I_m) and lags the applied voltage by 90°.

The second component of primary current (I_d) supplies the energy dissipated by the transformer core losses and is in phase with the applied voltage.

Figure 15-8 shows the vector diagram for the primary circuit of a transformer. The vector representing primary applied voltage (E_p) is plotted in standard position on the X-axis. The magnetizing current (I_m) is plotted downward on the Y-axis lagging the applied voltage by 90°. The exciting current I_e is the sum of these two component currents. Notice that since the loss current I_d is small, the exciting current I_e is made up almost entirely of magnetizing current and therefore lags the applied voltage by almost 90°.

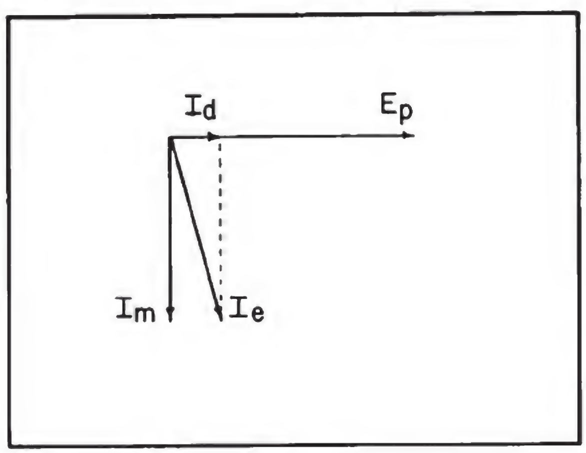

Figure 15-8 - Primary vector diagram.

Q4. What should be the ratio of magnetizing current to loss current in a well designed transformer?

15-6. Secondary Induced Voltage

To visualize how a voltage is induced into the secondary of a transformer, examine the left side of the diagram in Figure 15-9. As current flows into the top lead of the primary winding, lines of force are generated which produce a north pole at the top of the coil. During the time primary current is increasing, these lines of force expand outward from the primary and cut the secondary conductor. Since the lines are expanding outward from the primary, THE CONDUCTOR APPEARS TO BE MOVING INWARD WITH RESPECT TO THE LINES OF FORCE. This is shown by the vector labeled "motion" in Figure 15-9.

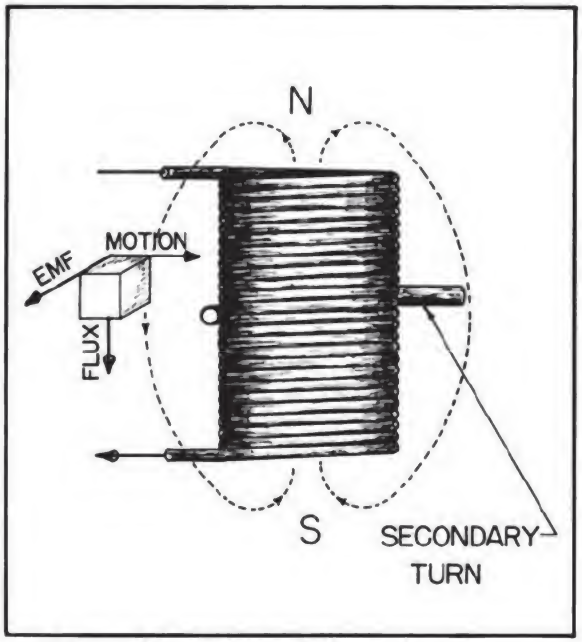

Figure 15-9 - Secondary induced voltage.

The direction of the voltage induced into the secondary conductor can be determined by the left-hand rule. Since the relative motion of the conductor is inward (to the right), and the lines of flux are direction downward, the EMF induced into the secondary is directed out of the paper on the left side of the coil. Notice that if the coil is viewed from above, the secondary induced EMF tends to force current through the secondary winding in a counter-clockwise direction while the EMF applied to the primary forces current through the primary in a clockwise direction. The voltage induced into a secondary turn is therefore identical to the counter voltage (CEMF) induced into an adjacent primary turn.

15-7. Winding Phase

The PHASE (polarity) of the secondary winding of a simple transformer depends on the direction of the windings and the arrangement of the connections to the external circuit. When the phasing of the windings is important to the operation of the circuit, dots are placed on the transformer schematic symbol at the ends of the windings which have the same instantaneous polarity. The use of phasing dots is illustrated in Figure 15-10.

In Figure 15-10A both the primary and secondary are wound from top to bottom in a clockwise direction, as viewed from above the windings. When constructed in this manner the top lead of the primary and the top lead of the secondary will have the SAME polarity. This is indicated by the dots on the transformer symbol.

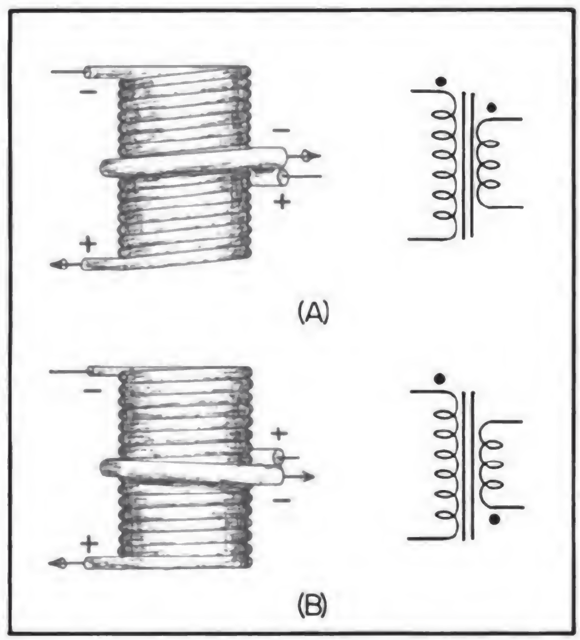

Figure 15-10 - Polarity depends on direction of winding.

Part (B) of the figure illustrates a transformer in which the primary and secondary are wound in opposite directions. As viewed from above the windings, the primary is wound in a clockwise direction from top to bottom while the secondary is wound in a counter-clockwise direction. Notice that the top leads of the primary and secondary have OPPOSITE polarities. This is shown in dot notation on the schematic beside the drawing of the windings. The polarity

A4. Since losses should be kept to a minimum the ratio of magnetizing current to loss current should be large.

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of the voltage at the terminals of the secondary thus depends on the direction in which the secondary is wound with respect to the primary.

Q5. Could both of the transformers in Figure 15-10 be used to invert the phase of a sine wave?

15-8. Coefficient of Coupling

The coefficient of coupling of a transformer is dependent on the portion of the total flux lines that cut both primary and secondary windings. Ideally, all the flux lines generated by the primary should cut the secondary and all the lines of the flux generated by the secondary should cut the primary. The coefficient of coupling would thus be one (unity), and maximum energy would be transferred from the primary to the secondary.

Practical power transformers use high permeability silicon steel cores and close spacing between the windings so as to provide a high coefficient of coupling.

Lines of flux generated by one winding which do not link the other winding are called LEAKAGE FLUX. Since leakage flux generated by the primary does not cut the secondary. It cannot induce a voltage into the secondary. The secondary induced voltage is therefore less than it would be if the leakage flux did not exist. Since the effect of leakage flux is to lower the secondary induced voltage, its effects can be duplicated by assuming an inductor to be connected in series with the primary. This series LEAKAGE INDUCTANCE is assumed to drop part of the applied voltage leaving less across the primary.

Q6. Considering the secondary induced voltage, can flux leakage be considered as a loss?

15-9. Voltage Ratio

The total voltage induced into the secondary winding of a power transformer is determined mainly by the RATIO of primary to secondary turns and the amount of voltage applied to the primary. This can be explained using the diagram in Figure 15-11. Part A of the diagram shows a transformer in which the primary consists of 10 turns of wire and the secondary consist of a single turn of wire. Notice that as the flux generated by the primary expands and collapses it cuts BOTH the primary turns

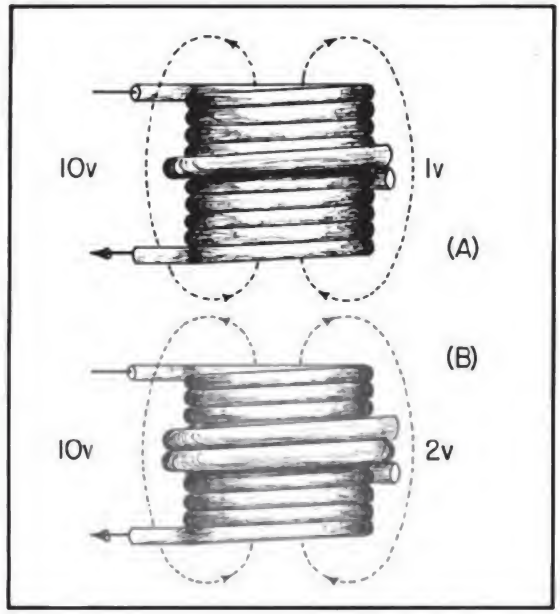


Figure 15-11 - Induced voltage depends on turns ratio.

and the secondary turn. Since the length of the wire in the secondary turn is approximately the same as the length of wire in each primary turn, THE VOLTAGE INDUCED INTO THE SECONDARY TURN WILL BE THE SAME AS THE CEMF INDUCED INTO EACH PRIMARY TURN.

If the voltage applied to the primary winding is 10 volts, the primary CEMF will be almost 10 volts. Thus, each primary turn will have an induced CEMF of approximately one-tenth of the total primary voltage, or one volt. Since the same flux lines cut the secondary as cut the primary, each secondary turn will have an induced EMF of one volt. The transformer in A of Figure 15-11 has only one turn on the secondary therefore the secondary voltage is one volt.

The transformer in part B of Figure 15-11 also has a 10 turn primary but the secondary consists of two turns of wire. Since the flux induces one volt per turn, the total secondary voltage is two volts. Notice that the volts per turn are the same for both primary and secondary windings.

This last statement can be used to derive an important relationship between the number of turns of each winding, and the voltages across the windings, as follows. The volts per turn (V/T) in the primary is obtained by dividing the voltage across the primary (E_p) by the number of turns on the primary (N_p).

$$V/T = \frac{E_p}{N_p} \qquad (15\text{-}1)$$

Transposing: (15-1)

$$E_p = N_p \times V/T \qquad (15\text{-}2)$$

The volts per turn across the secondary are:

$$V/T = \frac{E_s}{N_s} \qquad (15\text{-}3)$$

Transposing: (15-3)

$$E_s = N_s \times V/T \qquad (15\text{-}4)$$

Where: E_s = total secondary voltage in volts

N_s = number of secondary turns

V/T = secondary volts per turn

Dividing equation (15-2) by equation (15-4):

$$\frac{E_p}{E_s} = \frac{N_p x V/T}{N_s x V/T} \qquad (15\text{-}5)$$

Since secondary V/T equal primary V/T they cancel leaving:

$$\frac{E_p}{E_s} = \frac{N_p}{N_s} \qquad (15\text{-}6)$$

This important equation shows that the ratio of primary to secondary voltage is the same as the ratio of primary to secondary turns. If any three of the quantities in equation (15-6) are known, the fourth quantity can be computed.

Example. A transformer has 200 primary turns, 50 secondary turns, and a primary voltage of 120 volts. What is the secondary voltage?

Given: $N_p = 200$
$N_s = 50$
$E_p = 120$
$E_s = ?$

Solution: $$\frac{E_p}{E_s} = \frac{N_p}{N_s} \qquad (15\text{-}6)$$

Transposing for E_s:

$$E_s N_p = E_p N_s$$

$$E_s = \frac{E_p N_s}{N_p}$$

Substitution:

$$E_s = \frac{120 x 50}{200}$$

$$E_s = 30 \text{ volts}$$

Example. A technician has an iron core choke (coil) consisting of 400 turns. If the existing choke winding is to be used as a primary, how many turns must he wind for a secondary to construct a transformer in which the secondary voltage will be one-fifth the primary voltage?

Given: $N_p = 400$
$E_p = 5$
$E_s = 1$
$N_s = ?$

Solution: $$\frac{E_p}{E_s} = \frac{N_p}{N_s} \qquad (15\text{-}6)$$

Transposed: $$N_s = \frac{E_s N_p}{E_p}$$

Substitution: $$N_s = \frac{1 x 400}{5}$$

$$N_s = 80 \text{ turns}$$

The transformers in the two example problems have less secondary turns than primary turns, and as a result have less secondary voltage than primary voltage. A transformer in which the secondary voltage is less than the primary voltage is called a STEP-DOWN transformer. By constructing a transformer so that the secondary turns are greater in number than the primary turns, the secondary voltage will be greater than the primary voltage. A transformer in which the secondary voltage is greater than the primary voltage is called a STEP-UP transformer. The ratio of a one to four step-up transformer would be written as: 1:4 step-up.

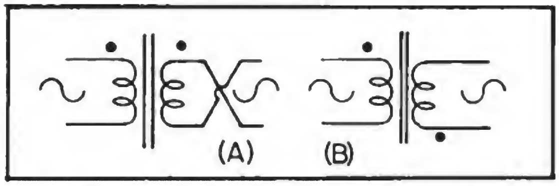
Q7. What could be done to the number of turns in the primary to reduce the secondary voltage?

Q8. What is the primary to secondary V/T ratio in a 1 to 3 step-up transformer?

EFFECTS OF LOAD

When a load device is connected to the secondary winding of a transformer, current is drawn from the secondary. The magnetic field produced by secondary current interacts with the primary field. This interaction results from the mutual inductance between the primary and secondary windings.

A5. Yes, by properly connecting the transformer leads as follows:



A6. Yes, but it is a wattless loss since it does not consume energy.

A7. Increase the number of primary turns.

A8. Approximately 1 to 1.

15-10. Mutual Flux

The total flux existing in the core of the transformer is common to both the primary and secondary, and is the means by which energy is transferred from the primary to the secondary winding. Since this flux links both windings it is called MUTUAL FLUX. The inductance which produces this flux is also common to both windings and is called MUTUAL INDUCTANCE.

Figure 15-12 shows the flux produced by the primary and secondary currents in a transformer at an instant of time when source current is flowing into the top lead of the primary winding. Notice that the flux lines (shown solid) generated by primary current produce a north pole at the top of the coil.

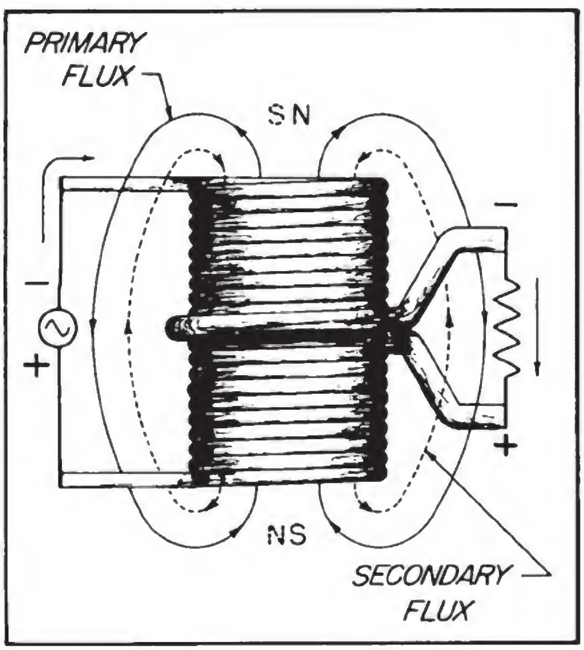


Figure 15-12 - Primary and secondary produce opposing flux.

When a load resistance is connected to the secondary winding the voltage induced into the secondary causes a flow of secondary current. This current produces a secondary flux field (dotted lines) which is in opposition to the primary flux field (Lenz's law). Thus, the secondary flux cancels some of the primary flux. With less flux surrounding the primary, the primary CEMF is reduced and more current is drawn from the source. The additional primary current generates more lines of flux nearly reestablishing the original number of total flux lines.

To summarize, as current is drawn from the secondary, total flux momentarily decreases, and primary current increases restoring the flux lines to almost their original number. Thus, over the normal operating range of load current, the total core flux does not change more than two or three percent.

Q9. What would happen if the applied voltage in Figure 15-12 was increased?

Q10. What change in mutual inductance occurs as secondary current is varied from minimum to maximum.

15-11. Current Ratio

The number of flux lines developed in a core is proportional to the ampere turns (magnetizing force) of the associated windings. The flux which exists in the core of a transformer surrounds both the primary and secondary. Since the flux is the same for both windings, the ampere turns (NI) must be the same for both, primary and secondary. Therefore:

$$N_pI_p = N_sI_s \qquad (15\text{-}7)$$

Dividing both sides of equation (15-7) by N_sI_p yields:

$$\frac{N_p}{N_s} = \frac{I_s}{I_p} \qquad (15\text{-}8)$$

Therefore:

$$\frac{E_p}{E_s} = \frac{I_s}{I_p} \qquad (15\text{-}9)$$

Where: I_p = primary current in amps
I_s = secondary current in amps

Notice that equations (15-8) and (15-9) show the current ratio to be the inverse of the turns ratio and voltage ratio. A transformer having less turns in the secondary than in the primary would step down the voltage, but would step up the current.

Example: A transformer has a 6 to 1 step-down voltage ratio. Find the secondary current if the primary current is 200 milliamps.

Given: $E_p = 6$
$E_s = 1$
$I_p = 0.2$ amps
$I_s = ?$

Solution:

$$\frac{E_p}{E_s} = \frac{I_s}{I_p} \qquad (15\text{-}9)$$

Transposing:

$$I_s = \frac{E_p I_p}{E_s} \qquad (15\text{-}10)$$

$$I_s = \frac{6 \times 0.2}{1}$$

$$I_s = 1.2 \text{ amps}$$

This example points out the fact that although the secondary voltage is one-sixth the primary voltage, the secondary current is six times the primary current.

15-12. Power Ratio

Basically, a transformer is a device used to transfer electrical power from one circuit to another, by means of a magnetic field. This transfer of power should be accomplished with a minimum loss of energy. To state this in another way, the power absorbed by the primary should be equal to the power delivered to the load by the secondary. The primary to secondary power ratio can be derived as follows:

$$\frac{E_p}{E_s} = \frac{I_s}{I_p} \qquad (15\text{-}9)$$

Cross multiplying:

$$E_p I_p = E_s I_s \qquad (15\text{-}11)$$

Since apparent power is equal to EI:

$$P_p = P_s \qquad (15\text{-}12)$$

Where: P_p = apparent primary power in volt-amperes
P_s = apparent secondary power in volt-amperes

Note that under ideal conditions the power taken from the source by the primary is equal to the power delivered to the load by the secondary.

Q11. How is it possible to have more current flowing in the secondary of a transformer than is flowing in the primary?

TRANSFORMER LOSSES

Practical power transformers, although highly efficient, are not perfect devices. Small power transformers used in electronics equipment range from 80 to 90 percent efficient, while large commercial powerline transformers may have efficiencies exceeding 98 percent.

Transformer losses are confined mainly to the windings and core, and are the result of an undesirable conversion of electrical energy into heat energy.

15-13. Copper Loss

Whenever a current is passed through a conductor, power is dissipated by the conductor in the form of heat. This power loss is due to the resistance of the conductor. The amount of power dissipated by the conductor, is directly proportional to the resistance of the wire, and to the square of the current through it. The greater the value of either resistance or current, the greater is the power dissipated.

The primary and secondary of a transformer are made of low resistance copper wire. The resistance of a given winding is a function of the diameter of the wire and its length. Power transformer windings have resistances ranging from less than one ohm to several hundred ohms. The power dissipated by winding resistance is called an (I^2R) LOSS, or COPPER LOSS.

Copper loss can be minimized by using the proper diameter wire. High current windings require large diameter wire, whereas small diameter wire can be used for the low current windings.

15-14. Eddy Current Loss

The core of a transformer is constructed of a ferromagnetic material. This material may not be a good conductor, but it does have the ability to conduct current.

Whenever the primary of an iron core transformer is energized by an alternating current source, a fluctuating magnetic field is produced, which will cut the conducting core material, and induce a voltage into it. The induced voltage causes random currents to flow through the core which dissipates power in the form of heat. These undesirable currents are called EDDY CURRENTS.

To minimize the losses resulting from eddy currents, transformer cores are LAMINATED. The laminations are made of thin strips of metal, which are pressed together to form the core. Each lamination is coated with varnish or some other insulating material. Since the thin insulated laminations do not provide an easy path for current, eddy current losses are greatly reduced.

A9. Primary current would increase, increasing the number of mutual flux lines thereby increasing secondary induced voltage.

A10. Ideally no change should occur.

A11. Equation (15-11) states that the product of primary current and voltage must equal the product of secondary current and voltage. Thus, if secondary voltage is less than primary voltage, secondary current must be greater than primary current.

15-15. Hysteresis Loss

When a magnetic field is passed through a core, the core material becomes magnetized. To become magnetized, the domains within the core must align themselves with the external field. If the direction of the field is reversed, the domains must turn so that their poles are aligned with the new direction of the external field.

Power transformers normally operate from either 60 cycle per second, or 400 cycle per second alternating current. Each tiny domain must re-align itself twice each cycle, or a total of 120 times a second when 60 cycle alternating current is used. The energy used to turn each domain is dissipated as heat within the iron core. This loss is called HYSTERESIS LOSS, and can be thought of as resulting from a kind of molecular friction. Hysteresis loss can be held to a small value by proper choice of core materials.

15-16. Transformer Efficiency

To compute the efficiency of a transformer the input and output power must be known. The input power is equal to the product of primary voltage and primary current. The output power is equal to the product of secondary voltage and secondary current. The difference between the input power and the output power represents the power consumed by the various transformer losses. The percent of efficiency of a transformer is calculated using the standard efficiency formula shown below.

$$\% \text{ Eff} = \frac{P_o}{P_{in}} \times 100 \qquad (15\text{-}13)$$

Where: $\%$ Eff = percent of efficiency
P_o = total output power of all the windings
P_{in} = total input power

Example. If the input power to a transformer is 650 volt-amperes and the output power is 610 watts, what is the percent of efficiency?

Solution:

$$\% \text{ Eff} = \frac{P_o}{P_{in}} \times 100$$

$$\% \text{ Eff} = \frac{610}{650} \times 100$$

$$\% \text{ Eff} = 93.7$$

The efficiency is approximately 93.7% with approximately 40 watts being wasted due to core and copper losses.

15-17. Transformer Ratings

When a transformer is utilized in a circuit, more than the simple turns ratio is considered by the designer. The power handling capacity of the primary and secondary windings must also be considered. The maximum voltage that can be applied to any winding is controlled by the type and thickness of the insulation used. The better (or thicker) the insulation between the windings, the higher will be the maximum voltage that can be applied to the windings. The current handling capacity of the transformer windings is controlled by the diameter of the wire used for the windings. If the current is excessive in the transformer winding, there is a higher than ordinary value of power dissipated across the winding in the form of heat. The heat generated inside the transformer may be sufficiently high to cause the insulation around the wires to melt. If the excessive current is permitted to flow, the transformer may be permanently damaged. The power handling capacity of a transformer is dependent upon its ability to dissipate heat. If the heat can safely be removed, the power handling capacity of the transformer can be increased. This is sometimes accomplished by immersing the transformer in oil or by the use of cooling fins. The power handling capacity of a transformer is measured in either the volt-ampere unit or the watt unit.

The popular frequencies used for transformers have been mentioned, but the effect of varying them above and below the specified frequency has not been discussed. If the frequency applied to a transformer is increased, the inductive reactance of the windings are increased causing a greater ac voltage drop across the windings and less across the load. However, increasing the frequency applied to a transformer does not damage it. If the frequency is decreased, the reactance of the windings decreases and the current through the transformer windings increases. If the decrease in frequency is sufficiently large to cause a significant increase in current, the transformer will be damaged. It is for this last reason that a transformer may be used at frequencies above its normal operating frequency, but never below.

EXERCISE 15

1. What is meant by the term inductive coupling?
2. What is the coefficient of coupling of two coils when all the flux generated by the first coil cuts all the turns of the second coil?
3. Why would an air core transformer be unsuitable for operation as a 60 cps power transformer?
4. Can you think of a reason why a transformer designed to operate from either 110 volts ac or 220 volts ac would have two primary windings? Explain.
5. Can you think of a reason why the primary winding of a power transformer would have several taps near one end? Explain.
6. Will a voltage be induced into the secondary of a transformer if dc is applied to the primary? Explain.
7. What effect would a decrease in secondary load impedance have on primary current?
8. Compute the following quantities, assuming the transformer in Figure 15-13 to have no losses. E_s, I_p, P_p, P_s and the turns, voltage, and current ratios.

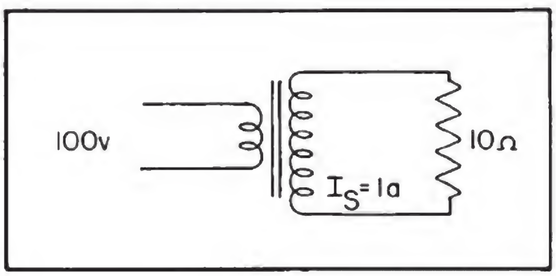


Figure 15-13.

9. Assuming all three transformer windings in Figure 15-14 to have the same number of turns, compute the voltage across the load resistor.

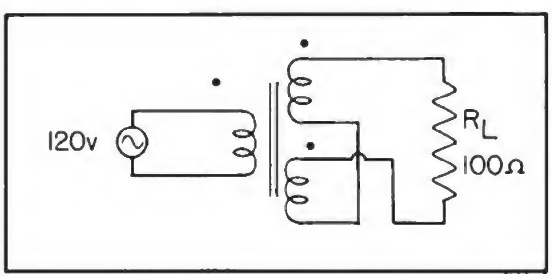


Figure 15-14 -

10. Assuming all three transformer windings in Figure 15-15 to have the same number of turns, compute the voltage across the load.

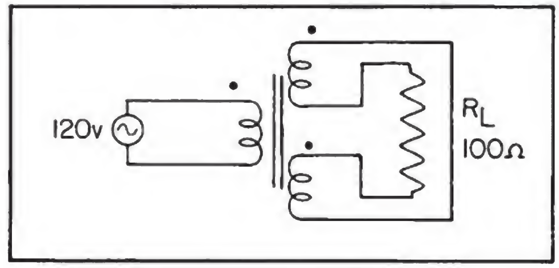


Figure 15-15

11. Compute the primary current for the transformer in Figure 15-16.

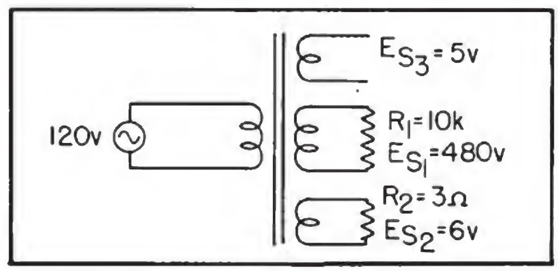


Figure 15-16

12. Compute the output voltage in Figure 15-17.

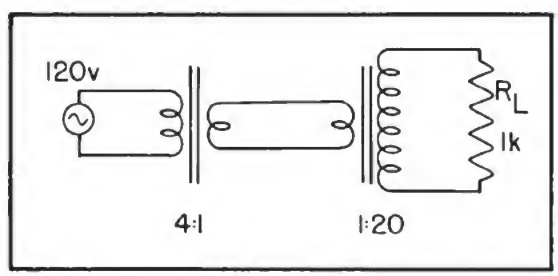


Figure 15-17

13. Describe the various transformer losses and how they can be reduced.

14. Graph the voltage across the resistor with respect to ground in Figure 15-18 for one cycle of input voltage.

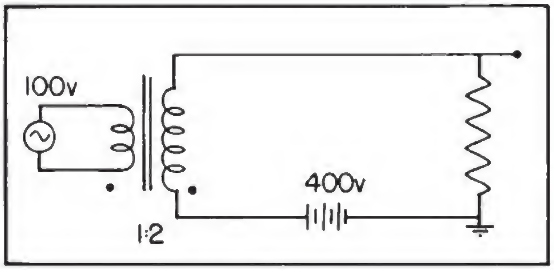


Figure 15-18

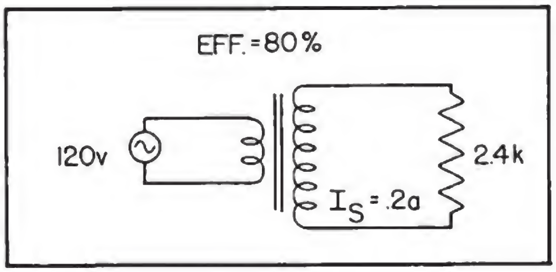


Figure 15-19

15. The transformer in Figure 15-19 has a primary winding resistance of 6 ohms and a secondary winding resistance of 250 ohms. Find the following:

Secondary voltage ______volts

Secondary power ______watts

Secondary copper loss______watts

Primary power ______volt-amperes

Primary current ______amps

Primary copper loss ______watts

Total core loss ______watts

CHAPTER 16

ELECTRON TUBE RECTIFIER CIRCUITS

Most electronic circuits require a steady source of dc voltage. This voltage may be produced by a dc generator or by changing ac to dc. In most cases, the more practical means is by the use of RECTIFIER CIRCUITS which change ac to dc. Most rectifier circuits use an electron tube called a DIODE. The diode is the simplest in structure and operation of all electron tubes. The diode must be given careful and detailed explanation because its operation is fundamental to the operation of all electron tubes that employ thermionic emission. If the current-voltage relationships pertaining to the high vacuum diode are understood, little difficulty will be encountered when more complex tubes are discussed.

The principle of the diode or two-element vacuum tube was discovered in 1883. While performing experiments with his recently invented incandescent light bulb; Thomas Edison had cause to insert a metal plate into the bulb near, but not touching, the hot filament wire. He then connected the metal plate through a sensitive meter to the positive terminal of the battery he was using to supply electrical energy to the bulb. To Edison's surprise, the meter indicated a current flow. A current flow in an apparently open circuit was unexplainable at that time, and the phenomenon was named the EDISON EFFECT. Edison himself did not realize the significance of the current flow.

A few years after Edison's discovery, Sir J. J. Thompson theorized that electrons were emitted by the hot wire filament, and were being attracted toward and collected by the positively charged metal plate. This theory won wide acceptance and is still used to explain electron tube operation.

ELECTRON EMISSION

16-1. Surface Barrier

Electron emission occurs when an electron leaves the surface of the material which contained it, and escapes into the space surrounding the material. Most metals have a large number of free electrons. Although they are called free electrons, they are free only in the sense that they can wander about within the lattice structure of the metal. The free electrons cannot normally escape from the surface of the metal.

Whenever the surface of a solid is placed in contact with liquid or a gas (air, etc.), a thin film develops on the surface of the solid. Theory predicts that in a perfect vacuum the film would not exist. However, since a perfect vacuum is not attainable some amount of surface film is always present. This is the same type of surface film which accounts for the surface tension of liquids such as water. The extremely thin surface film which develops on the exposed surfaces of metals acts to confine the atoms and free electrons within the metal. This thin film thus forms a SURFACE BARRIER through which the free electrons cannot penetrate.

Q1. If the surface film were removed would the surface barrier be removed?

16-2. Work Function

If a sufficient amount of energy is added to a free electron within a metal, the electron becomes capable of doing the amount of work necessary to break through the surface barrier. The amount of work required to cause an electron to surmount the surface barrier of a metal is called the WORK FUNCTION of the given metal.

Since the electrical energy contained by an electron is most conveniently measured in joules/coulomb (volts), the work function of a material is measured in units called ELECTRON VOLTS (ev). One electron volt of energy is the amount of energy gained by an electron as it is accelerated through an electrostatic field produced by a difference of potential of one volt. It is interesting to note that some of the particle accelerators used for nuclear research are capable of accelerating particles to energies much greater than one million electron volts.

The use of the electron volt can be illustrated by considering the work function of nickel. Nickel has a work function of 2.77 ev. Any free electron in a piece of nickel directed toward the surface barrier, and having kinetic energy of at least 2.77 ev (joules of energy/coulomb of charge), will escape through the surface barrier and be emitted.

A1. Yes. Because the surface film is the surface barrier.

The energy required to produce emission of an electron can be supplied to the electron in any of several forms such as heat energy (thermionic emission), light energy (photo emission), electrical energy (high field emission), or by collision with a high energy particle (secondary emission). One or more of these forms of emission are utilized in the operation of all electron tubes. The image orthicon TV camera tube for example, uses thermionic, photo, and secondary emission to produce the TV picture signal.

Q2. Compare the motion of two emitted electrons if one had just enough energy to overcome the surface barrier, and the other had substantially more than the necessary energy.

TYPES OF EMISSION

16-3. Thermionic Emission

THERMIONIC EMISSION is the process by which electrons gain enough energy by means of heat to escape from the surface of the emitting material. This is the type of emission most frequently employed in electron tubes.

Thermionic emission is commonly produced by heating the emitter of the tube with an electric current. The power dissipated, as the current flows through a wire filament, raises the temperature of the emitter to the point where electrons will be boiled from the surface of the emitting material.

Q3. Must the heat required to cause thermionic emission be supplied by an electric current?

16-4. Photo Emission

An emission of electrons can also be caused by light striking the surface of certain materials. This type of emission is called PHOTO EMISSION. The energy of the light rays striking the substance is imparted to the electrons near the surface. If the energy acquired by the electrons is sufficient, the kinetic energy thus gained will enable the electrons to overcome the surface barrier and the electrons will escape from the substance. The velocity with which the electrons are emitted is proportional to the frequency of the light energy striking the material. The higher the light frequency (shorter the wavelength), the greater is the velocity of the emitted electrons. The number of electrons emitted is directly proportional to the intensity of the light.

Materials to be used as photo emitters must have a low work function so that little energy is necessary to produce usable amounts of emitted electrons. Some of the more common materials that are sensitive to light are: cesium, selenium, zinc, and potassium. Two of the principal uses of photo emission are photoelectric cells and television camera tubes.

Q4. Since different materials have different work functions, what predictions could one make concerning the relationship between the type of material and the wavelength of light?

16-5. High Field Emission

To produce HIGH FIELD EMISSION a high concentration of positive charges is placed near the surface of the emitter. The intense electrostatic field developed between the emitter and the high positive charge literally rips the electrons from the surface of the material. High field emission is used in some electron tubes but is one of the less commonly used types.

16-6. Secondary Emission

Emission of electrons from a material caused by the impact of particles striking its surface is called SECONDARY EMISSION. If a stream of electrons flowing at a high velocity strikes a material, the force may be great enough to dislodge other electrons from the surface. The dislodged electrons are called SECONDARY ELECTRONS to distinguish them from the primary electrons which caused the secondary emission. Although secondary emission occurs to some extent in most tubes, it is used as a source of electrons in only a few specialized electron tubes.

EMITTER MATERIALS

16-7. Tungsten

The electrode or element which acts as the source of free electrons in an electron tube is called the CATHODE. Substances to be used as thermionic cathodes must have a low work function. In addition, they must not melt or vaporize at the temperatures required to produce the necessary amount of emission. At the operating temperature they must be able to withstand intense electric fields and mechanical vibration without breaking or sagging. These

stringent requirements eliminate all but a few substances as possible choices for cathode materials.

One of the first materials to be widely used for vacuum tube cathodes was tungsten. Tungsten has the advantage of mechanical ruggedness but must be heated to a very high temperature (2227°C) to obtain a sufficient amount of emission.

Because tungsten has a high work function (4.53 ev), its efficiency is poor. Emitter efficiency is measured in milliamperes of emission per watt of heating power (ma./watt). Tungsten emitters have an efficiency of approximately 7 ma./watt. Due to their low efficiency tungsten cathodes are seldom used in modern electron tubes.

16-8. Thoriated Tungsten

A significant improvement in efficiency can be obtained by coating a tungsten cathode with a thin layer of thorium. When so constructed the cathode is called a THORIATED TUNGSTEN cathode. This type of cathode has a work function of 2.86 ev, considerably lower than that of pure tungsten.

To form a thoriated tungsten cathode, a small amount of thorium is mixed with the tungsten. The cathode is then activated by operating it for a short period of time in a vacuum at a temperature above the normal operating temperature.

During activation a monatomic layer of thorium forms on the surface of the tungsten. It is this one-atom-thick layer of thorium which enhances the emission. The efficiency of a thoriated tungsten cathode ranges from 50 to 100 ma./watt. Due to the lower work function of thoriated tungsten, substantial amounts of emission can be obtained at a lower operating temperature (1700°C). Since fewer watts of heating power are required, the efficiency is increased.

16-9. Oxide Coated

The most efficient of all cathode structures is called an OXIDE COATED cathode. An oxide coated cathode is formed by placing a relatively thick layer of barium and strontium oxide on a nickel alloy wire or ribbon. This type of cathode need only be heated to a temperature of 750°C to produce a profuse supply of electrons. Emission efficiencies of over 150 ma./watt are obtainable with oxide coated cathodes. Because of their high efficiency, oxide coated cathodes are used extensively in low power and portable equipment where power drain must be limited to a small value.

Q5. Why might a metal such as tin, which melts at a temperature of about 232°C, not make a suitable emitter?

CATHODE CONSTRUCTION

16-10. Directly Heated

Thermionic cathodes are heated in one of two ways—directly, or indirectly. A DIRECTLY HEATED cathode is one in which the current used to supply the heat flows directly through the cathode emitting material. One type of directly heated cathode is illustrated in Figure 16-1A.

As shown, a thin piece of wire called a FILAMENT is suspended on an insulated support. The wire can be of tungsten, thoriated tungsten, or oxide coated nickel. A current from a battery or other source is passed through the wire, causing it to be heated to incandesence. When hot, the filament (or coating) emits electrons and can be used as a cathode.

The use of ac as a source for directly heated cathodes should be avoided in vacuum tubes operating with weak signals. Due to the small mass of the filament wire, the filament temperature rises and falls in step with the ac heating current, causing periodic fluctuations in the number of emitted electrons. In weak signal circuits this can introduce undesirable hum into the signal.

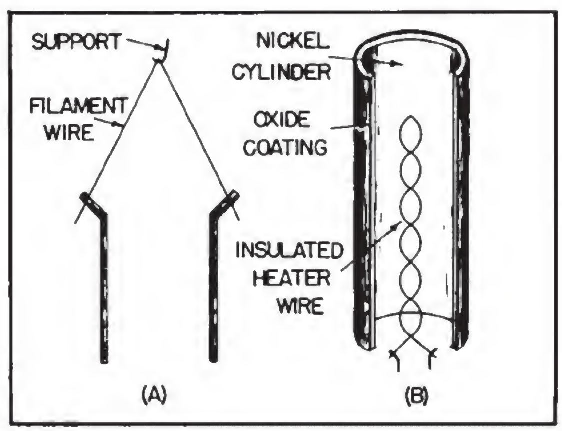


Figure 16-1 - Cathode construction.

16-11. Indirectly Heated

A relatively constant rate of emission with a fluctuating heater current can be obtained by employing an INDIRECTLY HEATED cathode. The construction of an indirectly heated cathode is illustrated in Figure 16-1B. In this type of cathode the heating current does not flow through the emitting material.

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A2. In the first case, the electron would travel to a point just outside the surface of the material. In the second case, the excess energy not used up in overcoming the surface barrier would be retained by the electron as kinetic energy of motion, and the electron would travel away from the material.

A3. No. Heat supplied from any source can produce thermionic emission, however, heating the emitter with an electric current is usually the most convenient.

A4. The conclusion could be drawn that all materials are not sensitive to the same wavelengths (colors) of light. Some photosensitive materials produce maximum emission for infrared radiation, while others produce peak emission in the ultraviolet region, etc.

A5. The emitter would melt before sufficient emission would be obtained.

The cathode consists of a thin nickel cylinder which is coated on the outside with barium and strontium oxides. A tungsten or tungsten alloy wire called a HEATER is placed inside the nickel cylinder. This wire is used as a heating element only and does not supply any part of the emission in the tube.

The oxide coated nickel cylinder is maintained at the correct temperature by the heat radiated from the heater. In cathodes where ceramic insulating material is packed around the heater wire, part of the heat is supplied by heat conduction through the ceramic.

Due to the large mass of this type of cathode, as compared to a filament type cathode, the emitting material stays at a relatively constant temperature regardless of the 60 cycle per second variation in heater current. As a result of the isolation between heater and emitter, ac hum is minimized. Most modern low power tubes use indirectly heated cathodes.

Q6. What type of cathode structure would be used for the vacuum tubes in a piece of equipment which must be ready for operation as soon as it is turned on?

DIODE CONSTRUCTION

16-12. Placement of Elements

As the name implied, the DIODE vacuum tube contains two electrodes or elements. These electrodes are called the CATHODE and PLATE. The plate collects the electrons which are emitted by the cathode.

Physically, the cathode is placed in the center of the tube structure and is surrounded by the plate. Examples of directly and indirectly heated diodes are shown in the cut-away views of Figure 16-2. Notice that in both types of construction the plate is placed so as to intercept most of the electrons emitted by the cathode.

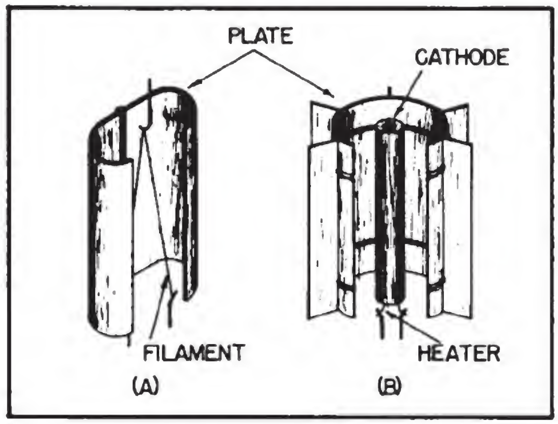

Figure 16-2 - Typical construction of directly and indirectly heated diodes.

Since the purpose of the plate is to collect electrons, it is made of a material which does not emit electrons readily. The plate must also be capable of radiating the heat generated within itself during operation of the tube. Diode plates are constructed of carbonized nickel, nickel plated steel, or copper.

When assembled, the diode electrodes are placed inside a glass or metal envelope. To prevent the cathode emitting surfaces from becoming contaminated, and to allow the electrons freedom of motion without collisions with air molecules, the glass envelope is highly evacuated (hence the name vacuum tube).

To remove any gas left after evacuation a small quantity of magnesium or barium, called a "getter", is used. The getter is ignited by means of a high frequency coil which is placed around the glass envelope of the electron tube. The high frequency field induces eddy currents in the metal within the tube. These eddy currents heat up a small metal cap which contains the getter material and a small charge of gunpowder. This heat fires the getter which combines with gas left in the tube to form a silvery deposit on the inner walls of the envelope. In metal envelope tubes the getter is fired by other means. A completely assembled diode vacuum tube is shown in Figure 16-3.

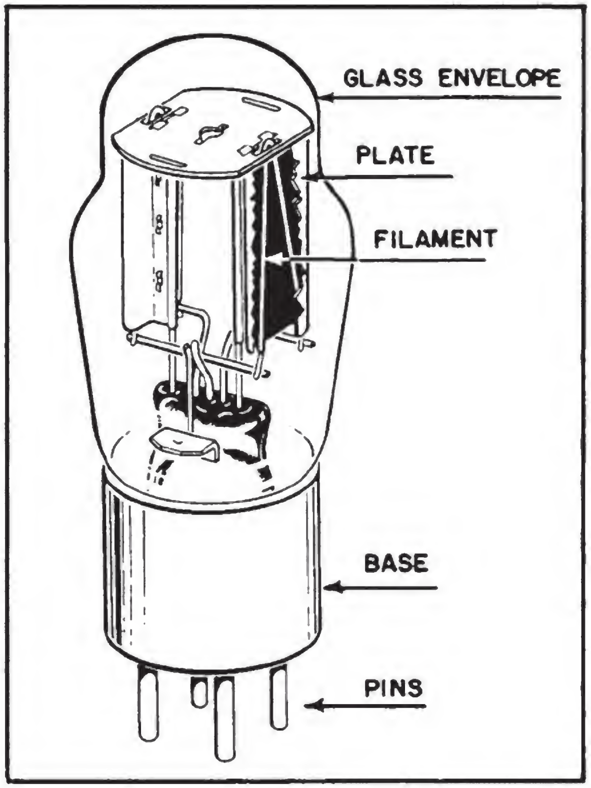

Figure 16-3 - Assembled diode vacuum tube.

Q7. Why might metal fins be added to the plate of a tube? (See Figure 16-2B.)

16-13. Tube Bases

As a general rule, vacuum tubes do not have as long a life expectancy as resistors, capacitors, and other circuit components. To provide for easy removal and replacement, the base of the tube is constructed in the form of a plug which is inserted into a socket on the chassis. The electrical connections between the tube elements and the circuit is completed through the plug terminals which are called PINS.

Each type of tube base has some kind of guide or KEY to prevent the tube from being plugged into the socket improperly. The location of the pins on a four prong tube is shown in Figure 16-3.

There are various types of tube bases which contain different numbers and sizes of pins. Some of these types are shown in Figure 16-4. For ease of circuit tracing, the tube pins are assigned numbers. When looking at the BOTTOM of the tube or socket, the pins are numbered in a CLOCKWISE direction beginning with pin number one at the key or guide. The pin numbering systems for several types of tubes are shown in Figure 16-4.

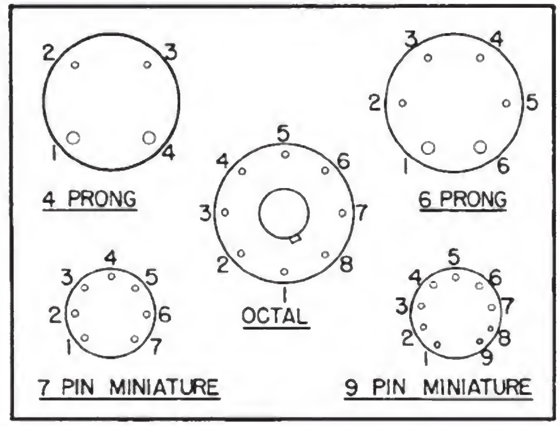

Figure 16-4 - Base types and numbering systems.

Each electron tube is identified by symbols printed on the tube. This system, developed in 1933, is still in general use. Although the majority of small-sized vacuum tube types adhere to this system, some exceptions do exist.

The symbols printed on the tube are called the TUBE NUMBER and consist of a series of numbers and letters. The first symbol in the tube number is a number which tells the approximate filament or heater voltage. For example, a 6SN7 and a 50L6 require heater voltage of 6.3 volts ac/dc and 50 volts ac/dc respectively. The second symbol is a letter which designates the function of the tube. Rectifier tubes for example are usually assigned letters near the end of the alphabet (U, V, W, X, Y, and Z).

The third symbol is a number which indicates how many of the total base pins must be connected for proper operation of the tube (not always applicable). As an example, the tube designation 5U4 indicates that the filament requires 5 volts, the (U) indicates that the tube is a rectifier, and the (4) indicates that four of the eight base pins are actually needed to operate the tube. To obtain specific information on any given type of tube, a tube manual should be consulted.

The schematic symbols used to represent diode tubes are shown in Figure 16-5. In many cases two or more diodes may be included in the same glass or metal envelope. This is done to conserve space. A tube which contains two diode sections is referred to as a DUO-DIODE or a TWIN DIODE. The schematic symbols for typical twin diodes are shown in Figure 16-5.

A6. A directly heated cathode because the thin wire filament is capable of rapid changes in temperature and thus can heat quickly.

A7. To provide a larger surface area so that heat can be radiated from the plate more effectively.

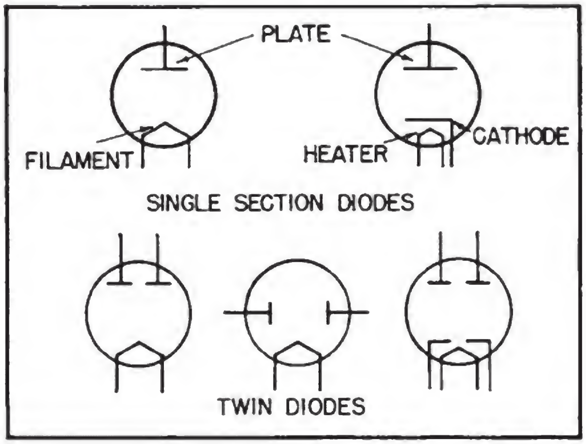

Figure 16-5 - Schematic symbols used for diodes.

Q8. At the beginning of this section it was stated that most tubes do not have a long operating life. What would probably be the most common cause of tube failure in a simple diode?

DIODE ELECTRICAL CHARACTERISTICS

In many ways the diode vacuum tube can be compared to a resistor. If the proper polarity of voltage is placed across a diode, a current will flow through the diode. The magnitude of this current is dependent on the amount of applied voltage and the opposition which the diode presents to the source. As current flows through the diode, power is dissipated in the form of heat. Like a carbon resistor, each diode has a maximum power dissipation rating which must not be exceeded.

The diode differs from an ordinary resistor in that the diode is a UNILATERAL RESISTANCE. The common resistor is BILATERAL, meaning that it will conduct current in two directions. The diode, on the other hand, can only conduct current in one direction—from cathode to plate. It is the unilateral or one direction characteristic which makes the diode so useful.

16-14. Conditions With Zero Plate Voltage

To properly operate a diode vacuum tube, two supply voltages are required. One of these supply voltages is applied to the heater or filament circuit, the other to the plate-cathode circuit. Originally, the only available voltage sources were batteries. The battery used to supply power to the filament or heater was called the "A" battery. The battery used to supply power to the plate of the tube was called the "B" battery.

Even though in modern electronics batteries are seldom used for other than portable equipment, the letter designations are still used. The filament or heater source (normally a transformer winding) is called the "A" supply and the source of plate voltage is called the "B" supply.

Figure 16-6 shows a circuit consisting of a diode, a source of heater voltage, and an ammeter which is connected between plate and cathode. Since no source of voltage is connected between plate and cathode, the plate is at zero potential with respect to the cathode.

If the switch in the heater circuit is closed, current will flow through the heater circuit, heating the cathode. As the cathode approaches normal operating temperature, emission begins and electrons are thrown out of the emitting material and into the evacuated space surrounding the cathode.

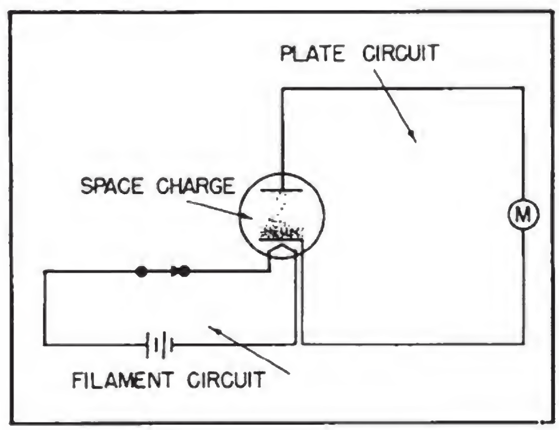

Figure 16-6 - Diode tube with zero plate voltage.

The majority of the emitted electrons have low velocities and do not travel far from the cathode surface. These electrons form an invisible but dense cloud of electrons which hover over the surface of the cathode. This cloud of negative charge is called the SPACE CHARGE.

A few of the more violently expelled electrons have velocities sufficient to carry them beyond the space charge to the plate electrode.

After striking the plate the electrons flow from the plate through the ammeter (M) and thence to the cathode where they are re-emitted. Thus, if a complete path is provided between plate and cathode, a minute flow of current will exist.

Due to the extremely small number of electrons which are able to reach the plate, this flow of current is not large enough to be significant and is normally neglected. The ammeter in the plate to cathode circuit of Figure 16-6 would not indicate a noticeable flow of current. Practically speaking, then, a diode will not conduct current when the plate to cathode voltage is zero.

Q9. When the plate voltage is zero and the space charge is completely formed, does emission of electrons from the cathode still exist?

16-15. Conditions With Negative Plate Voltage

The operation of a diode with negative plate voltage will be examined with the aid of Figure 16-7. The plate supply voltage is obtained from a "B" battery (E_{bb}) connected between the plate and cathode as shown in the diagram. The

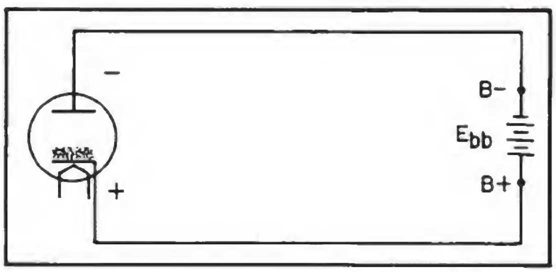

Figure 16-7 - Diode with negative plate voltage.

negative terminal of the battery (B-) is connected to the plate of the tube and the positive terminal of the battery (B+) is connected to the cathode. As is quite often done, the heater circuit is not shown to simplify the drawing.

The application of a negative voltage to the plate of the tube causes an electrostatic field to exist between the plate and cathode. Since the plate is negative with respect to the cathode, the direction of this field is such as to repel electrons away from the plate and toward the cathode. Due to the plate's inability to emit electrons, no current can flow through the tube. Thus, the overall effect of a negative plate voltage is to repel the electrons in the space charge, causing them to move closer to the cathode. When the plate of a diode is negative with respect to its cathode, the diode acts as an open circuit.

16-16. Conditions With Positive Plate Voltage

If the plate of a diode tube is made positive with respect to the cathode, as shown in Figure 16-8, an electrostatic field will be established between plate and cathode. The direction of this field is such as to accelerate the electrons near the outer edge of the space charge and attract them to the plate. Upon striking the plate the electrons are attracted to the positive terminal of the battery. This flow of electrons from the plate of the tube to the positive terminal of the battery is called PLATE CURRENT (I_b).

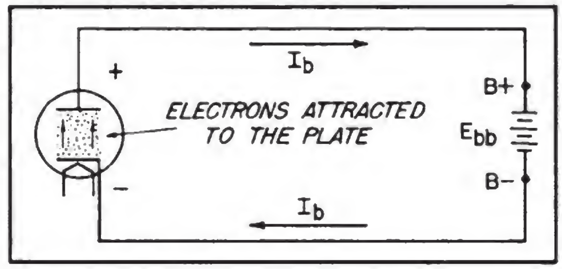

Figure 16-8 - Diode with positive plate voltage.

For each electron removed from the space charge by the plate, one electron is supplied to the space charge by the cathode. The space charge thus acts as a reservior from which the plate can draw electrons.

Since the number of electrons entering the plate is the same as the number of electrons leaving the cathode, the plate and cathode currents are identical. The tube and battery therefore constitute a simple series circuit in which the tube acts as a resistance and the current is the same in all parts of the circuit.

As long as the space charge reservoir of electrons exists around the cathode, the amount of plate current depends entirely on the amount of positive voltage applied to the plate. If the plate voltage is increased, the plate current will increase.

As a result of the effects of the space charge, the resistance of the diode is not constant and is dependent on the amount of current through the tube. Since the resistance of a diode changes with changes in current, the volt-ampere characteristic of a diode is not a straight line. Due to this, a diode is a NON-LINEAR device, wherein equal increases of source voltage do not produce equal increases of plate current. The important features of a diode can be summed up as follows:

1. A diode contains two elements called the cathode and plate.
2. A cloud of electrons called the space charge surrounds the cathode.

A8. The filament eventually burns through or the emission falls below that required for proper operation.

A9. Yes, but for each electron emitted into the space charge, one of the space charge electrons will fall back to the cathode maintaining a constant average number of electrons in the space charge.

---

3. A diode will conduct current in one direction—from cathode to plate.
4. A diode will conduct only when its plate is positive with respect to its cathode.
5. The amount of plate current depends on the amount of voltage applied between cathode and plate.
6. The resistance of a diode changes with changes in plate current.
7. A diode acts as a non-linear resistance.

VOLT-AMPERE CHARACTERISTIC

16-17. Obtaining The Curve

When a study of the characteristics of electron tubes is made, CHARACTERISTIC CURVES are used to make a more thorough investigation of tube operation. Of the many curves that can be plotted, the plate voltage (E_b) versus plate current (I_b) curve is the most useful. This plot is called the VOLT-AMPERE or E_b-I_b CURVE.

To obtain a volt-ampere curve, the diode to be studied is connected to a variable dc source as shown in Figure 16-9B. If the plate voltage of the diode is increased in steps and the corresponding increases in plate current are plotted, the graph shown in Figure 16-9A is obtained. If the plate is made slightly positive with respect to the cathode, plate current will begin to flow. As plate voltage is increased the attracting force exerted on the electrons in the space charge increases, resulting in an increase in plate current. The curve can be seen to consist of three distinct regions; 0 to A, A to B, and B to C. Notice that a large amount of curvature exists from points 0 through A and B through C, but the curve is very linear from A to B. As the curve is plotted, a point is finally reached (point C) where a further increase in plate voltage no longer produces an increase in plate current. At this point, the reservoir of electrons in the space charge is exhausted and the plate is attracting the electrons as fast as they are emitted from the cathode. This condition is called SATURATION and at this point the upper limit of the tube's conduction capabilities have been reached.

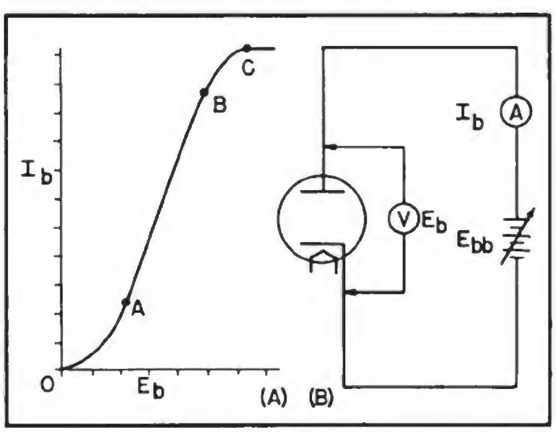

Figure 16-9 - Diode volt-ampere characteristic.

Q10. What determines the density of the space charge?

PLATE RESISTANCE

16-18. DC Plate Resistance

When a diode is connected directly across a battery (such that the plate is made positive) current will flow through the diode. The magnitude of the current flow through the tube is determined by the type of tube used and the value of the voltage applied to it. The voltage-current characteristics are determined by the construction of the tube and the type of emitter used. The important fact to note is that the current flow through the tube is some finite value. Because of the limit placed on the value of current, the tube is effectively offering opposition to the flow of current. The opposition offered to the flow of direct current in an electron tube is called DC PLATE RESISTANCE. DC plate resistance is measured in ohms, and the symbol used to represent it is R_b. This resistance is thought of as existing within the tube from plate to cathode.

To compute the dc resistance of a diode the plate voltage and the corresponding plate current must be known. The values of current and voltage can be obtained from the volt-ampere curve or from an actual circuit. Once values have been obtained for plate current and voltage, the dc plate resistance can be computed using Ohm's law. The formula for R_b is:

$$R_b = \frac{E_b}{I_b} \qquad (16\text{-}1)$$

where: R_b = dc plate resistance in ohms

E_b = the potential between plate and cathode in volts

I_b = the plate current in amperes

The voltage dropped across the tube is designated by the symbol E_b, and is called the plate voltage. Plate voltage is always the difference in potential between plate and cathode. It should not be confused with the applied voltage E_{bb}. However, there are occasions where the difference of potential between plate and cathode is the applied voltage. When this happens E_{bb} and E_b are the same value.

The dc resistance of a diode is not constant throughout the operating current range of the tube. This can be verified by calculating the R_b at several different points along the volt-ampere curve shown in Figure 16-10.

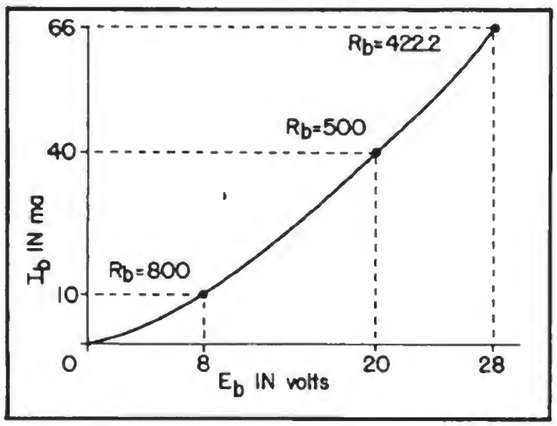

Figure 16-10 - E_b-I_b curve for a 6H6 using one diode section.

For example, at a plate voltage of 8 volts the curve shows the plate current to be 10 milliamps. At this point on the curve the R_b is:

$$R_b = \frac{E_b}{I_b} \tag{16-1}$$

$$R_b = \frac{8}{10 \times 10^{-3}}$$

$$R_b = 800 \text{ ohms}$$

At a plate voltage of 20 volts and a plate current of 40 milliamps the R_b is 500 ohms. Notice that, generally speaking, the higher the plate current becomes, the lower will be the dc plate resistance.

16-19. AC Plate Resistance

The term AC PLATE RESISTANCE is defined as the opposition offered to the flow of alternating current by an electron tube. The symbol used to designate ac plate resistance is (r_p). The r_p of a diode tube is determined by using the following formula:

$$r_p = \frac{\Delta e_b}{\Delta i_b} \tag{16-2}$$

where: r_p = ac plate resistance in ohms

Δe_b = the change in instantaneous voltage at the plate

Δi_b = the change in instantaneous current through the tube

Note that the ac plate resistance is computed using small change (Δ) in plate current and voltage. The values of current and voltage required for equation (16-2) can be obtained from the volt-ampere curve or from an actual circuit.

It is interesting to compare the dc and ac plate resistance of a diode. At a plate voltage of 8 volts the 6H6 diode was found to have a dc resistance of 800 ohms.

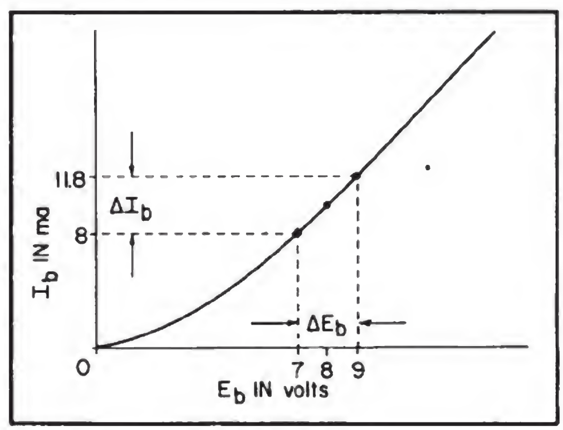

Figure 16-11 - Solving for diode r_p.

To find the ac plate resistance at this point on the curve, the change in plate current is obtained for a change in plate voltage, centered about an average plate voltage of 8 volts. Referring to Figure 16-11, assume the tube to have a plate voltage of 7 volts. The corresponding plate current is 8 ma. If the plate voltage is increased to 9 volts the plate current will increase to 11.8 ma. Thus, Δe_b = 2 volts and Δi_b = 3.8 ma. Computing the r_p:

A10. For a constant cathode temperature and emission rate, the space charge density decreases as the plate voltage is increased in a positive direction. This is due to the larger number of electrons drawn from the space charge at higher plate voltages.

$$r_p = \frac{\Delta e_b}{\Delta i_b} \qquad (16\text{-}2)$$

$$r_p = \frac{2}{3.8 \times 10^{-3}}$$

$$r_p = 526 \text{ ohms}$$

The average r_p at a plate voltage of 8 volts is therefore approximately 526 ohms, 274 ohms less than the dc plate resistance. At higher values of plate current the r_p is lower than 526 ohms, being approximately 400 ohms at a plate voltage of 18 volts.

Q11. What causes the ac and dc resistance of a diode to decrease as plate current increases?

16-20. Diode Ratings

Diodes are classified in two groups—power diodes and signal diodes. Power diodes are the ones used in power supplies and other applications where the currents and voltages are of a large magnitude.

In many applications the plate current of a diode occurs in pulses. During the time the pulse of current flows, the plate of the tube heats up as a result of the current. When the tube is not conducting between pulses, heat is radiated allowing the plate to cool.

Due to the pulse type nature of the plate current waveform, the diode is given two current ratings, called the MAXIMUM PEAK PLATE CURRENT RATING, and the MAXIMUM AVERAGE PLATE CURRENT RATING. The peak plate current capabilities of a given tube depend on the emission available from the cathode. The maximum allowable average current depends on the amount of heat which can be safely dissipated by the plate. A 5Y3 twin diode for example, has a peak current rating of 440 ma. However, when the current pulses are averaged over a number of cycles, the average current must not exceed about 125 ma. or the tube may be damaged from the excess heat developed.

In addition to the two current ratings discussed above, a diode also has a PEAK INVERSE VOLTAGE RATING, abbreviated (PIV). This rating determines the maximum negative voltage which may be applied to the plate with respect to the cathode, and is a function of the physical spacing of these two elements. If the (PIV) rating is exceeded an arc may occur between plate and cathode causing damage to the tube.

RECTIFICATION

The transmission of electrical energy over great distances was made economical through the use of alternating current. Alternating current could be transmitted over great distances with a minimum of power dissipation within the transmission line.

Most electron tubes and many other electrical devices require a steady source of dc voltage. This voltage may be provided by a dc generator or by changing ac to dc. The process of changing ac to dc is called RECTIFICATION. The devices used to accomplish rectification are called RECTIFIERS.

16-21. The Process of Rectification

Since a diode vacuum tube will pass current in one direction only, it is ideally suited for converting alternating current to direct current. If a sine wave of voltage is applied to a diode, the diode will conduct ONLY DURING THE POSITIVE ALTERNATION OF VOLTAGE when the plate is made positive with respect to the cathode.

Figure 16-12 shows a diode connected across the 120 volt ac line. During the positive alternation of source voltage, the sine wave applied to the tube makes the plate positive with respect to the cathode. Since this polarity of plate voltage causes the diode to conduct, a current will flow in the circuit. Current will flow from the negative supply lead, through the milliammeter and tube, to the positive supply lead. This cur-

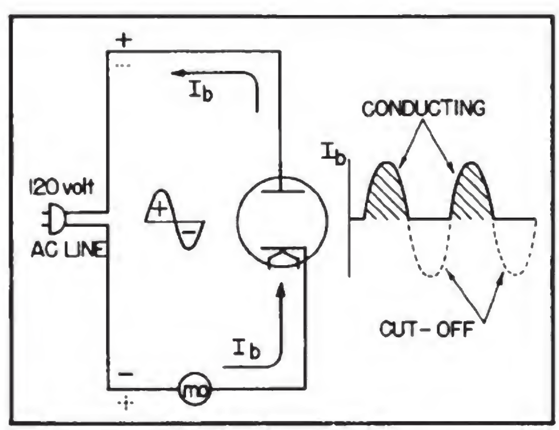

Figure 16-12 - Simple diode rectifier.

rent will exist during the entire period of time that the plate is positive with respect to the cathode, or for the first 180° of the input sine wave.

During the negative alternation of plate voltage (dotted polarity signs) the plate is driven negative and the tube cannot conduct. When conditions are such that the tube cannot conduct, the tube is said to be CUT-OFF. The tube will be cut-off and no current will flow in the circuit during the entire negative alternation.

For each cycle of input voltage the tube will conduct for 180° and will be cut-off for the other 180°. The circuit current will therefore have the appearance of a series of positive half cycles (shown shaded). Notice that although the current is in the form of pulses, the current always flows through the circuit IN THE SAME DIRECTION. Current which flows in pulses but is always in the same direction is called PULSATING DC. The diode has thus RECTIFIED the input voltage.

16-22. A Practical Half-Wave Rectifier

To utilize the diode as a rectifier, it is connected in series with the load device through which the direct current is to flow. Since in many cases it is necessary to have a rectified voltage which is greater (or smaller) than the source voltage, the rectifier plate circuit is often supplied power from a step-up (or step-down) transformer. A schematic diagram of a complete half-wave rectifier circuit is shown in Figure 16-13.

The transformer has two secondary windings. The lower winding supplies high voltage to the plate and cathode of the diode. Notice that the cathode of the diode is connected to the secondary winding through the load resistor (R_L). Any current flowing through the tube will also flow through the load resistor causing a voltage to be developed across it. The magnitude of the voltage dropped across the load resistor is directly proportional to the current flowing through it.

The operation of the half-wave rectifier is as follows: when switch S_1 is closed, the primary of the transformer is energized, and voltage will be coupled by flux linkage to both secondary windings. The voltage induced into the heater winding will cause current to flow through the heater, and the cathode will rise to emitting temperature after a few cycles of input voltage have been applied. The voltage induced into the high voltage winding will alternate, causing the plate of the diode to be positive with respect to the cathode on one alternation, and then negative with respect to the cathode of the other alternation.

The operation of a half-wave rectifier circuit

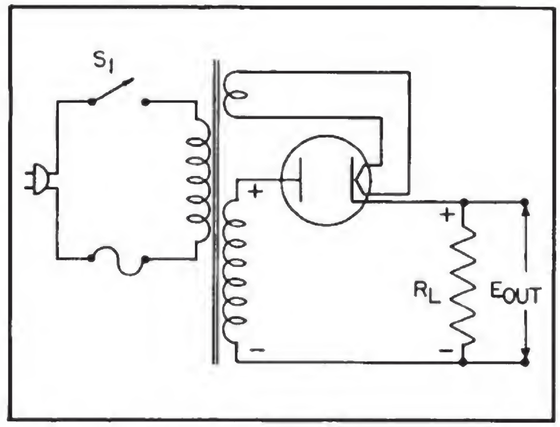

Figure 16-13 - Half-wave rectifier circuit.

will be analyzed using the circuit shown in Figure 16-14. In this figure the circuit has been redrawn to emphasize the fact that the rectifier tube and the load resistor form a simple series circuit connected across the transformer high voltage secondary.

At zero degrees on the sine wave of secondary voltage the applied voltage is zero and therefore the circuit current is zero. An instant later the top end of the secondary winding becomes slightly positive and current begins to flow in the circuit. Since the diode tube and load resistor form a series circuit, the same current flows through both the tube and resistor. This current will produce voltage drops across the load resistor and tube which have the polarities shown in Figure 16-14. Since the plate resistance of the diode is approximately 500 ohms, about 95 percent of the applied voltage will be dropped across the load resistor and only about 5 percent will be dropped across the tube.

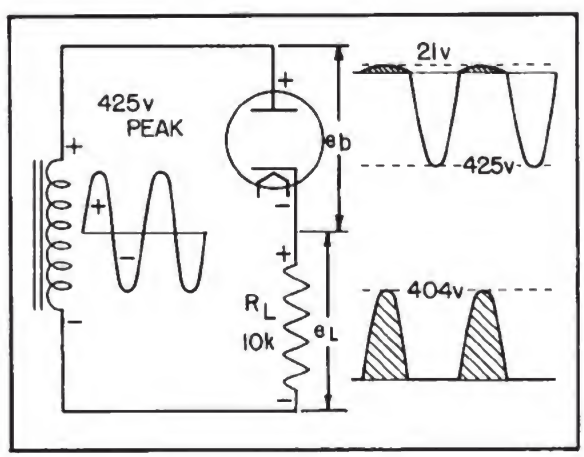

Figure 16-14 - Rectifier circuit and voltage waveforms.

A11. At higher currents the density of the space charge is reduced, allowing the emitted electrons to travel from cathode to plate more easily.

As the positive alternation of applied voltage progresses, the voltage applied to the tube and resistor increases steadily. At 30° the applied sine wave attains one-half the peak value or 212.5 volts. Of the 212.5 volts applied approximately 202 volts are dropped across R_L and the remaining 10.5 volts are dropped across the tube.

At 90° the applied sine wave reaches its peak value and the voltage applied to the circuit is 425 volts. Of this total, about 404 volts are dropped across R_L and 21 volts are dropped across the tube. From 90° to 180° the voltage applied to the circuit decreases from 425 volts to zero volts, causing the tube and load voltages to drop to zero.

During the negative alternation of applied voltage the tube cannot conduct and no current flows in the circuit. Since there is no current flow through R_L, the load voltage remains at zero volts throughout the negative alternation. During this time the entire negative alternation is dropped across the tube. This is in accordance with Kirchhoff's law, from which the following equation is derived.

$$e_L + e_b = e_a \qquad (16\text{-}3)$$

This equation states that at any instant of time the sum of the load voltage and diode voltage must equal the applied voltage.

The voltage waveforms for the tube and load resistor are shown in Figure 16-14. Notice that for practical purposes all the positive alternations appear across the load resistor while all the negative alternations are dropped across the rectifier tube.

Q12. Which component in a simple half-wave rectifier would have the largest instantaneous voltage across it—the diode or the load resistance?

16-23. Waveform Analysis

The overall objective of any rectifier circuit is to convert ac to the proper type of dc required by the load. Although the simple half-wave rectifier provides a uni-directional load current, this current occurs in the form of pulses.

Since a half-wave rectifier tube conducts once during each full cycle of input voltage, the frequency of the pulses is the same as the frequency of the input sinewave. The output pulse frequency is called the RIPPLE FREQUENCY. If the rectifier circuit is supplied power from the 60 cycle per second ac line voltage, 60 pulses of load current will occur each second. Therefore, THE RIPPLE FREQUENCY OF A HALF-WAVE RECTIFIER IS THE SAME AS THE LINE FREQUENCY.

If a series of current pulses like those obtained from a half-wave rectifier are applied to a load resistance, some average amount of power will be dissipated over a given period of time. This average dc power is determined by the amplitude of the pulses and the time delay between pulses. The higher the peak amplitude of the pulses or the less the time between pulses, the greater will be the average dc power supplied to the load. To determine average dc power it is necessary to obtain the average value of the pulses of load voltage and current.

Since the current and voltage waveforms in a half-wave rectifier circuit are essentially half sine waves, a conversion factor can be developed on this basis. In Chapter 8, the electrical average value of a complete sine wave of voltage or current was found to be equal to 0.637 times its peak or maximum value. Since the load voltage consists of a series of half sine waves of voltage, the average value of load voltage can be computed by multiplying the maximum value of the voltage pulse by one-half of 0.637. Stated mathematically:

$$E_{avg} = 0.318\ E_{max} \qquad (16\text{-}4)$$

where: E_{avg} = the average load voltage

E_{max} = the peak value of the load voltage pulse

In most applications the drop across the rectifier tube is small compared to the load voltage and E_{max} in equation (16-4) can be assumed to be equal to the peak value of the applied sine wave.

Since the load current has the same wave shape as load voltage, equation (16-4) can be modified so as to apply to load current. Thus,

$$I_{avg} = 0.318\ I_{max} \qquad (16\text{-}5)$$

where: I_{avg} = the average load current

I_{max} = the peak load current

Figure 16-15 shows the relationship between the maximum (peak) and average values of current and voltage for a half-wave rectifier cir-

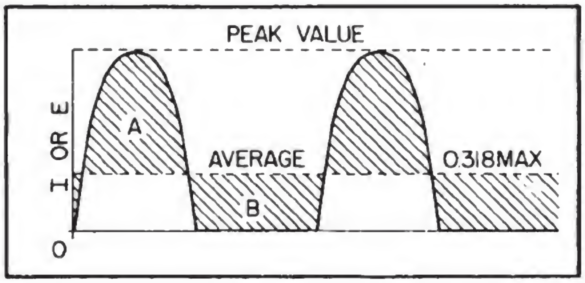

Figure 16-15 - Peak and average values for half-wave rectifier.

cuit. If a line is drawn through the rectified waveform at a point 0.318 of the distance from zero to maximum, the waveform will be divided such that area A is equal to area B. Thus, the pulses of current or voltage have the same effect on the load as a steady current or voltage having a value equal to 0.318 of the peak values of the pulses.

The half-wave rectifier utilizes the transformer during only one-half of the cycle, and therefore for a given size transformer, less power can be developed than if the transformer were utilized on both halves of the cycle. In other words, if a considerable amount of power is to be developed in the load, the half-wave transformer must be relatively large compared with what it would have to be if both halves of the cycle were utilized. This disadvantage limits the use of the half-wave rectifier to applications that require a very small current drain. The half-wave rectifier is widely used for commercial ac-dc radio receivers and for the accelerating voltage supplies of oscilloscopes.

Q-13. If the load resistance in a half-wave rectifier circuit is decreased, what happens to the amplitude and frequency of the current pulses?

16-24. Basic Full-Wave Rectifier Circuit

A full-wave rectifier is a device that has two or more diodes so arranged that the load current flows in the same direction during each half-cycle of the ac supply.

A schematic diagram of a simple full-wave rectifier circuit is shown in Figure 16-16. The source voltage for the two rectifier tubes V_1 and V_2 are supplied by a power transformer having a center-tapped high voltage secondary. The center-tap divides the secondary winding into two equal parts so that W_1 acts as the source for V_1 and W_2 acts as the source for V_2. The connections to the diodes are arranged so that the diodes will conduct on alternate half-cycles.

During one alternation of the secondary voltage the polarities across the secondary of the power transformer will be as shown in Figure 16-16. The source for diode V_2 is the voltage

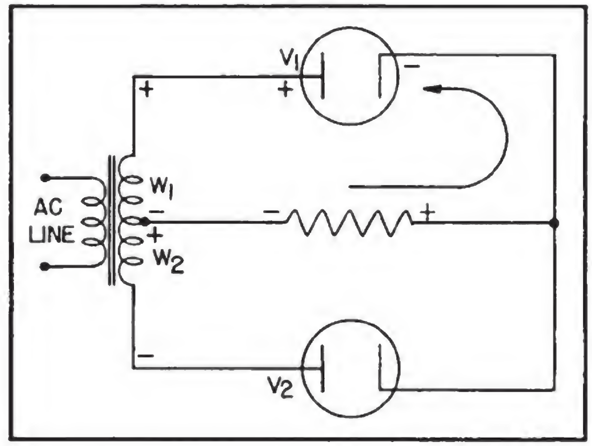

Figure 16-16 - Simple full-wave rectifier circuit.

induced in the lower half of the transformer secondary W_2. At the instant of time shown the plate voltage on V_2 is negative and V_2 cannot conduct.

Throughout the period of time during which the plate of V_2 is negative, the plate of V_1 is positive. This is illustrated in Figure 16-16 by the polarity signs across W_1 which acts as a source for V_1. Since the plate of V_1 is positive, it will conduct, causing current flow through the load resistor in the direction shown.

On the next half-cycle of secondary voltage, the polarities across W_1 and W_2 will reverse, as shown in Figure 16-17. During this alternation, the plate of V_1 is driven negative, and V_1 cannot conduct.

For the period of time that the plate of V_1 is negative, the plate of V_2 is positive, permitting V_2 to conduct. Notice that the plate current of V_2 passes through the load resistor in the same direction as did the plate current of V_1 on the previous half-cycle. In this circuit arrangement, a pulse of load current flows during each alternation of every input cycle. Since both alternations of the input voltage cycle are used, the circuit is called a FULL-WAVE rectifier.

Q14. What would result if the voltages on each side of the secondary center tap were not equal?

A12. The diode. At the peak of the negative alternation the full secondary voltage is dropped across the tube. At the peak of the positive alternation the applied voltage divides across the tube and the load.

A13. The amplitude of the pulses will increase and the pulse frequency will remain the same.

A14. The diodes would not conduct equally. The diode having the larger voltage would carry more of the load current.

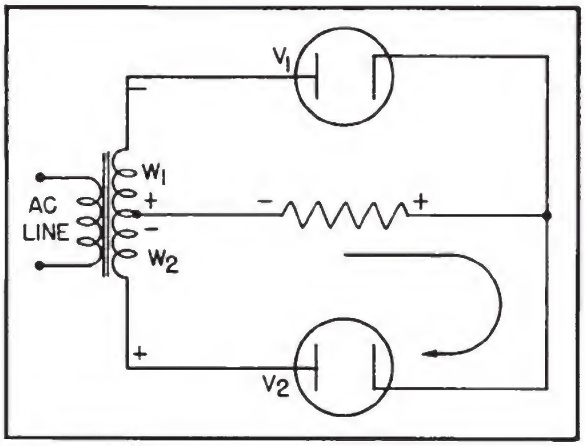

Figure 16-17 - Conduction path on second alternation.

16-25. Practical Full-Wave Circuit

To conserve space on the chassis the two diode tubes in the full-wave circuit can be replaced with a single twin diode. This only simplifies the wiring, and does not alter the operation of the circuit in any way.

The schematic diagram of a typical full-wave rectifier circuit using a twin diode is illustrated in Figure 16-18. Since a directly heated rectifier tube is used, the load resistance is connected between the filament-type cathode and the center-tap of the high voltage secondary. To simplify the wiring, the metal chassis is used to complete the connection between the bottom of the load resistance and the secondary center-tap. This is shown schematically by grounding each of these two points. An additional secondary winding (X, X) on the power transformer supplies heater voltage to other tubes that may be contained in the equipment.

The operation of a full-wave rectifier circuit using a twin diode will be explained with aid of Figure 16-18. The individual alterna-

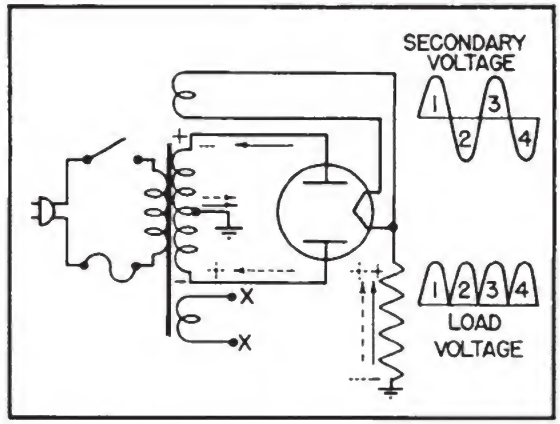

Figure 16-18 - Complete full-wave rectifier.

tions of the total secondary voltage have been numbered for identification.

During positive alternation number 1, the top end of the secondary is positive with respect to ground, and the bottom end of the secondary is negative with respect to ground. Only the upper diode has the necessary positive plate voltage required for conduction. Current will flow from ground, up through the load resistor (solid arrows) to the cathode, from the cathode to the upper diode plate, down through the top half of the transformer secondary to the center-tap, and back to the bottom of the load resistor by way of the metal chassis. This current develops a pulse of voltage across the load resistor which makes the top of the resistor positive with respect to ground. The waveform across the resistor is shown by the load voltage alternation marked "1" in the diagram.

Upon completion of the positive alternation, the polarities across the secondary winding reverse. This makes the plate of the top diode negative causing the top diode to cut off. The bottom diode plate becomes positive and conduction occurs over the path marked by the dotted arrows. The important fact to note about the circuit arrangement is that current flows through the load resistance in the same direction for both positive and negative alternations of the applied sine wave.

When the output waveform from the full-wave rectifier is examined, it is seen to consist of two pulses of current or voltage for each cycle of input voltage. The ripple frequency at the output of a full-wave rectifier is therefore TWICE THE LINE FREQUENCY.

The higher ripple frequency at the output of a full-wave rectifier is a distinct advantage. Due to this higher pulse frequency, the output more closely approximates pure dc. As will be

seen in the next chapter, the full-wave output is easier to filter, or smooth out, than is the half-wave rectifier output.

In terms of the peak value, the average value of current or voltage at the output of a full-wave rectifier is twice as great as the average current or voltage at the output of a half-wave rectifier. The relationship between peak and average values is illustrated in Figure 16-19.

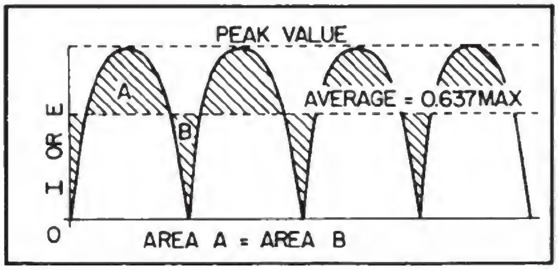

Figure 16-19 - Peak and average values for full-wave rectifier.

Since the output waveform is essentially a sine wave with both alternations having the same polarity, the average current or voltage is 63.7% of the peak current or voltage. As an equation:

$$E_{avg} = 0.637\ E_{max} \qquad (8\text{-}22)$$

where: E_{avg} = the average load voltage

E_{max} = the peak value of the load voltage pulse

and:

$$I_{avg} = 0.637\ I_{max} \qquad (8\text{-}23)$$

where: I_{avg} = the average load current

I_{max} = the peak value of the load current pulse.

Example. The total voltage across the high voltage secondary of a transformer used to supply a full-wave rectifier is 600 volts. Neglecting the drop across the rectifier tube, find the average load voltage.

Solution: Since the total secondary voltage is 600 volts, each diode is supplied one-half this value, or 300 volts. As the secondary voltage is an RMS value, the peak load voltage is:

$$E_{max} = 1.414\ E \qquad (8\text{-}18)$$

$$E_{max} = 1.414 \times 300$$

$$E_{max} = 424 \text{ volts}$$

The average load voltage is:

$$E_{avg} = 0.637\ E_{max} \qquad (8\text{-}22)$$

$$E_{avg} = 0.637 \times 424$$

$$E_{avg} = 270 \text{ volts}$$

Q15. For a given diode plate supply voltage, which type of rectifier circuit (half, full-wave) produces the largest average output voltage?

16-26. The Bridge Rectifier

If four diodes are connected as shown in Figure 16-20, the circuit is called a BRIDGE RECTIFIER. The input to the circuit is applied to diagonally opposite corners of the network, and the output is taken from the remaining two corners.

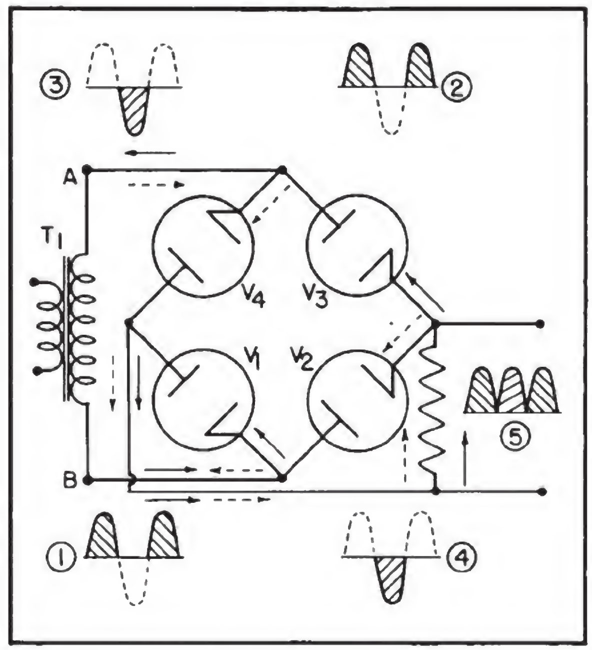

Figure 16-20 - The bridge rectifier.

During one half-cycle of the applied voltage in Figure 16-20, point A becomes positive with respect to point B by the amount of voltage induced into the secondary of the transformer. During this time, the voltage across AB may be considered to be impressed across V_1, load resistor R, and V_3 in series. The voltage applied across these tubes makes their plates more positive than their cathodes, and a current flows in the path indicated by the solid arrows. The waveform of this circuit is shown in (1) and (2).

One-half cycle later the polarity across the

A15. Under equivalent conditions, the average output voltage of the full-wave rectifier is twice the average output of the half-wave rectifier.

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secondary reverses, making the plates of V_1 and V_3 negative with respect to their cathodes. At the same time the plates of V_2 and V_4 become positive with respect to their cathodes, and current flows in the direction indicated by the dashed arrows. The current through the external load R is always in the same direction. This current, in flowing through R, develops a voltage corresponding to that shown in (5). The bridge rectifier is a full-wave rectifier since current flows through the load during both half cycles of the applied alternating voltage.

One advantage of a bridge rectifier over a conventional full-wave rectifier is that with a given transformer the bridge circuit produces a voltage output nearly twice that of the full-wave circuit. This may be shown by assigning values to some of the components in Figure 16-21. Assume that the same transformer is used in both circuits. The peak voltage developed between X and Y is one thousand volts in both circuits. In the full-wave circuit, the peak voltage from the center tap to either X or Y is five hundred volts. Since only one diode can conduct at any instant, the maximum voltage that can be rectified at any instant is five hundred volts. Therefore, the maximum voltage that will appear across the load resistor will be near, but will never exceed five hundred volts. In the bridge circuit of Figure 16-21B, the maximum voltage that can be rectified is the full secondary voltage which is one thousand volts. Therefore, the peak output voltage across the load resistor will be nearly a thousand volts. Thus the full-wave bridge circuit produces a higher output voltage than the conventional full-wave rectifier with the same transformer.

A second advantage of the bridge rectifier circuit is the low ratio of peak inverse voltage to average output voltage. For this reason bridge rectifier circuits employing vacuum tubes are used in high-voltage power supply applications.

If directly heated diodes are used in a bridge rectifier, three separate filament transformers are required. This is due to the different potentials existing at the filaments of the diodes. The filaments of V_2 and V_3 in Figure 16-22 are at the same potential, but the filament of V_1 is at a different potential from either V_2 or V_4. The three filament transformers must be well insulated from each other, and from ground, because of the high potentials to which they are subjected. The use of indirectly heated diodes would solve the filament transformer problem, but the high potential difference between cathode and heater would be likely to result in arcing.

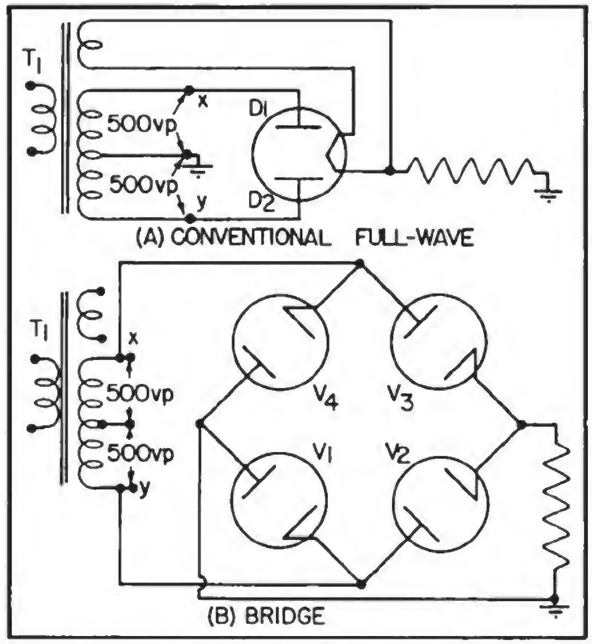

Figure 16-21 - Comparison of conventional full-wave, and bridge rectifiers.

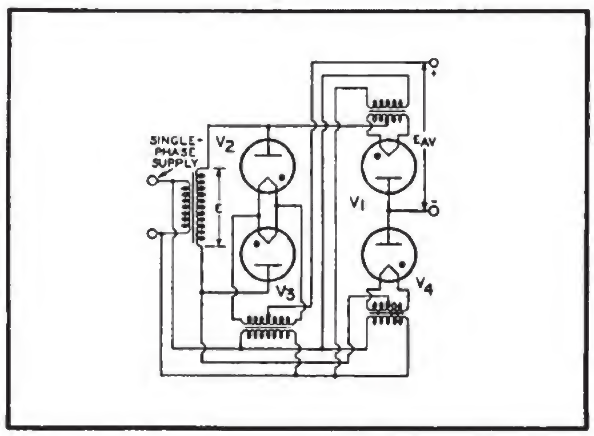

Figure 16-22 - Bridge rectifier circuit with filament transformers.

EXERCISE 16

1. Describe the events which lead to the emission of an electron from the surface of a material.
2. List the types of energy that can cause emission.
3. What is a "surface barrier" as it pertains to emission?
4. What is the "work function" of a material?
5. What should be the "work function" of a good emitter?
6. What is a thoriated tungsten emitter?
7. Describe the construction of an indirectly heated, oxide coated cathode.
8. Describe the creation of a space charge.
9. Why is the diode tube evacuated?
10. Name the parts of a diode, and describe their location and function.
11. Describe the effects on a diode if plate voltage is (a) zero, (b) negative, (c) positive.
12. What is the PIV rating of a diode?
13. What is rectification?
14. Explain the operation of a half-wave rectifier.
15. Explain the operation of a full-wave rectifier.
16. Why are three filament transformers required for a bridge rectifier using directly heated tubes?

CHAPTER 17

FILTER CIRCUITS

All electronic equipment consists of a combination of individual circuits, each of which is dependent upon particular values of voltage and current for their proper operation. To ensure such a condition, it is often necessary to separate direct currents from alternating currents or alternating currents of a specific range of frequencies from alternating currents outside of a desired frequency band. A device capable of performing this function of frequency discrimination is known as a filter.

For the proper operation of amplifiers, oscillators, modulators and other electronic devices, it is necessary to provide a smooth dc voltage. A pure dc voltage, such as supplied by a battery is very desirable. However, the dc voltage required in many electronic applications are much higher than a practical battery can supply. Therefore a combination of a rectifier circuit and a filter circuit is necessary to produce a dc voltage that is reasonably smooth. If the pulsating dc voltage that is present at the output of a rectifier was directly applied to a vacuum tube, the pulsations would cause improper operation of the tube. To suppress the magnitude of the variations in voltage, the rectifier output voltage is first applied to a filter circuit where various combinations of inductors, capacitors and sometimes resistors produce the desired degree of ripple suppression. In the following discussion ripple voltage and the action of various types of filter circuits will be discussed.

RIPPLE VOLTAGE

The polarity of a rectifier's output voltage does not reverse, but its magnitude varies above and below an average value as the successive pulses of energy are delivered to the load. In Figure 17-1, the average voltage is shown as the line that divides the wave-form so that area A equals area B. The variation of voltage about this average value is called RIPPLE.

17-1. Ripple Frequency

The number of variations above and below the average voltage each second is known as the ripple frequency. The ripple frequency of a rectifier's output voltage is determined by the rectifier configuration and the frequency of the line voltage. In single phase systems, the ripple frequency of a half-wave rectifier equals the line frequency while the ripple frequency of the full wave and bridge configurations is twice the line frequency as shown in Figure 17-1. Ripple frequency plays a major role in determining the size of filter components, since X_L and X_C vary with frequency.

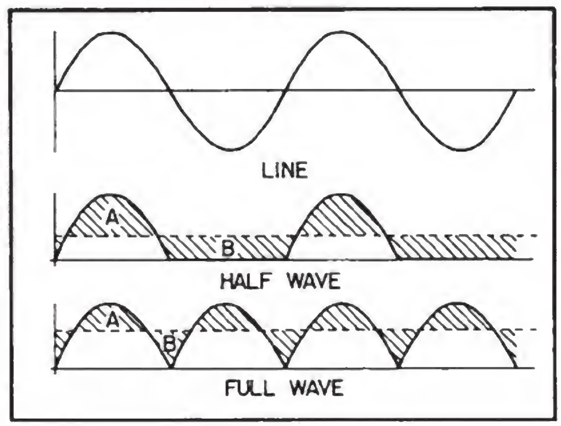

Figure 17-1 - Unfiltered rectifier outputs.

Q1. How does the ripple frequency of a rectifier having a single phase 60 cycle input compare with the ripple frequency of a rectifier having a single phase 400 cycle input?

17-2. Ripple Amplitude

The output voltage of any rectifier is composed of a dc component and an ac component. For most applications the ac component or ripple voltage must be reduced to a very low amplitude. The amount of ripple that can be tolerated varies with different applications of electron tubes.

The amount of ripple amplitude is expressed as percentage of ripple. The percentage of ripple is 100 times the ratio of the RMS value of the ripple voltage at the output of a filter, to the average value, E_o, of the total output voltage. Figure 17-2 indicates graphically how the percentage of ripple may be determined. It is assumed that the ripple voltage is a sine wave since the more practical filtered outputs of a

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A1. 400 cycle input has a greater ripple frequency.

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rectifier will approximate the form of the sine wave. Expressed as an equation:

$$\text{Percentage of ripple} = \frac{E_{RMS} \times 100}{E_o} \qquad (17\text{-}1)$$

where: $E_{rms} = 0.707$ of e_p and e_p is the peak value of the ripple voltage.

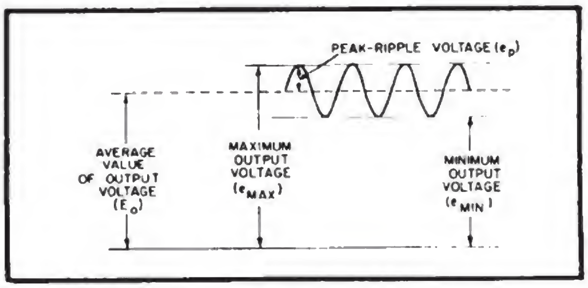

Figure 17-2 - Percentage of ripple.

Example. What is the percentage of ripple in the output of a power supply if a dc voltmeter across the output reads 200 volts and an ac voltmeter reads 2 volts?

Given: $E_{RMS} = 2$ volts

$E_o = 200$ volts

% of ripple = ?

Solution:

$$\% \text{ of ripple} = 100 \times \frac{E_{RMS}}{E_o}$$

$$\% \text{ of ripple} = 100 \times \frac{2}{200}$$

$$\% \text{ of ripple} = \frac{200}{200}$$

$$\% \text{ of ripple} = 1\%$$

Q2. If the ac voltmeter of the above example reads a higher value, how is the percentage of ripple affected?

TYPES OF FILTERS

17-3. Capacitance Filter

A ripple voltage exists in the output of a rectifier because of the rectifier supplies pulses of energy to the load. A capacitor connected in parallel with the load resistance will reduce variations in the output by storing energy during the conduction time of the rectifier and releasing energy to the load during the cut-off time of the rectifier.

The action of a capacitance filter is illustrated in Figure 17-3, where a half-wave rectifier with its output applied to a capacitor is shown. The peak ac input is 100 volts. As the first positive half cycle is applied to the plate of V_1, the tube conducts and capacitor C_1 begins to charge. The rate of charging C_1 is limited only by the reactance of the transformer secondary winding and the plate resistance of the rectifier. Therefore, the capacitor voltage rises nearly as fast as the input pulse.

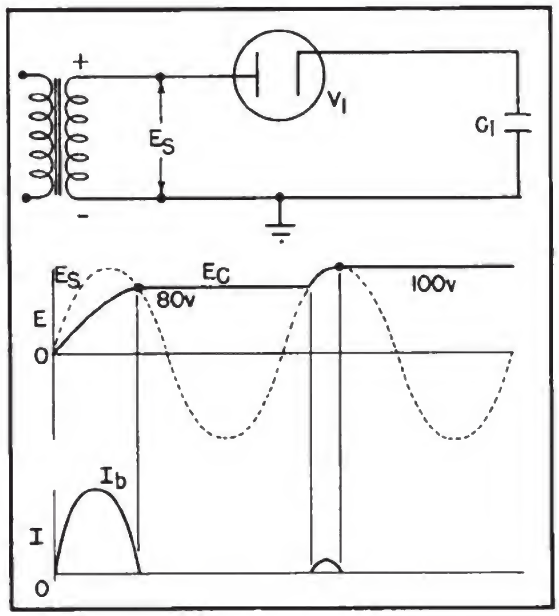

Figure 17-3 - Half wave rectifier (no load).

When the input voltage starts to decrease, the voltage of the capacitor does not follow. Instead, the voltage remains constant since the capacitor does not have a discharge path.

Assume that C_1 charges to 80 volts during the first half of the input cycle. Since C_1 has no discharge path, the cathode of V_1 will remain at a positive 80 volt potential ($E_k - E_C$). The plate-to-ground voltage must therefore exceed +80 volts before V_1 will again conduct. During the positive half of the second input cycle when the plate-to-ground voltage reaches a value greater than a +80 volts. V_1 goes into conduction and allows further charging of C_1. Assuming that the capacitor C_1 now charges to 100

volts, V_1 can no longer conduct since the plate can no longer become positive with respect to the cathode. The output across the capacitor is now pure dc equal to the peak value of the input.

Q3. For simplification, it was assumed that the capacitor C_1 charged to a peak value of 100 volts (Figure 17-3). Is this assumption completely accurate? Explain.

Q4. Refer to Figure 17-3, what is the maximum possible instantaneous voltage across the rectifier? Explain.

If the action of the plate current is analyzed, it can be noted that at the beginning of the charge time of C_1, plate current (Ib) is impeded only by the reactance of the transformer winding and the plate resistance of the tube. Therefore, Ib is initially at a relatively high value. As the capacitor continues its charge Ib decreases in value since the voltage across the capacitor causes the value of Ek to approach the plate-to-ground voltage. During the second positive half of the input voltage, plate current does not flow until the plate voltage is above Ek. Since C_1 is already partially charged, plate-to-cathode potential is lower and the resultant plate current is lower.

A similar analysis can be made of the action of a capacitor filter upon a full wave rectifier. Operation is the same with the exception that E_C will reach a value that approximates the peak value of E input much faster. This is illustrated in Figure 17-4.

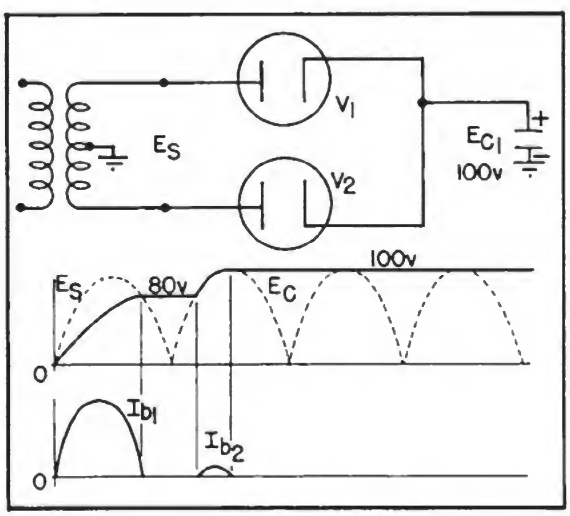

Figure 17-4 - Full wave rectifier (no load).

Q5. Refer to Figure 17-4, what is the maximum possible instantaneous voltage across either rectifier? Explain.

If a load resistance is connected in parallel with the capacitor, as indicated in Figure 17-5, a change will be noted on the voltage appearing across the capacitor. Since C_1 and R_L are in parallel, Ec is equal to ER_L and any variations in E_C will also appear across R_L.

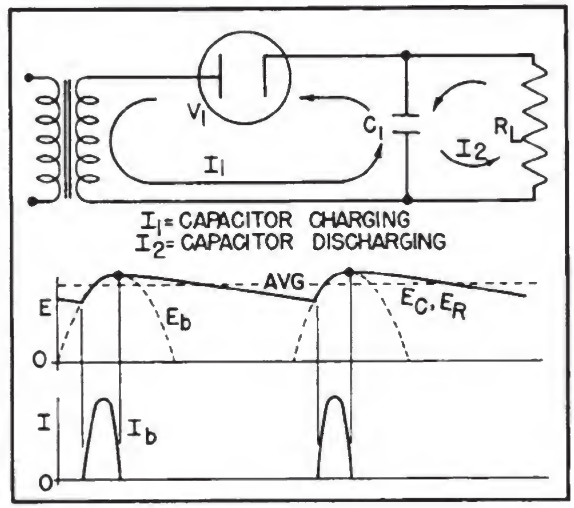

Figure 17-5 - Half wave rectifier--resistive load.

Assume that C1 has been charged to the peak input voltage. During the time V_1 no longer conducts, C_1 can discharge through R_L. Since C_1 and R_L are large, the time constant is long and E_c will decrease slowly. When the next positive pulse appears on the plate of V_1 and plate-to-ground voltage is greater than E_c, V_1 will again conduct, allowing C_1 to again charge to peak input voltage. The entire process continues producing the wave shape shown in Figure 17-5. The average dc output is less than the peak input voltage, but is greater than that which would exist without the addition of the capacitance filter. The unfiltered half-wave rectifier would have an average voltage equal to .318 E peak. With C_1 in the circuit, the ripple component has been reduced considerably. Therefore, the filtered average dc voltage output would be larger, its exact value is dependent upon the value of the capacitor and the size of the load. As the value of the filter capacitor or the load resistance is increased, the average dc output voltage is increased.

The circuit of Figure 17-6 is a full wave rectifier having the same peak input as the half-wave rectifier (100V). The values of C_1 and R_L and consequently the time constant are also the same as in Figure 17-5. Since there is less time between input pulses, E_C cannot decrease

A2. The percentage of ripple is increased.

A3. No. A small amount of voltage is dropped across the plate resistance of the tube.

A4. 200 Volts. When V_1 does not conduct the instantaneous peak of the secondary voltage will aid the capacitor voltage.

A5. 200 Volts. The instantaneous peak of the secondary voltage will aid the capacitor voltage of the non-conducting diode.

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as much as it did in the previous circuit. This results in a higher average dc output and a lower ripple amplitude. Since E_C is higher, at the time of conduction, E_b will be lower, producing a lower peak I_b.

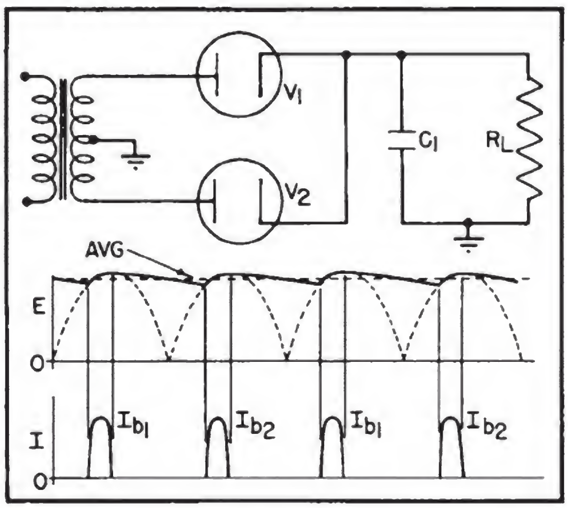

Figure 17-6 - Full wave rectifier - high resistance load.

Q6. The plate voltage of three diode tubes is supplied by the power source indicated in Figure 17-6. If the plate connecting wire within one of the tubes becomes open, what effect could be noted upon the output of the power source?

The effect of a decrease in the size of the load resistance is illustrated in Figure 17-7. Since the analysis is true for both half wave and full wave circuits, only the full wave circuit will be considered.

Compare Figure 17-7 with Figure 17-6. The decrease in R_L has caused the time constant to become shorter. E_C can consequently decrease to a lower value in the same amount of time. The average dc voltage decreases and the amplitude of the ripple increases. Also since E_C drops to a lower value I_b increases.

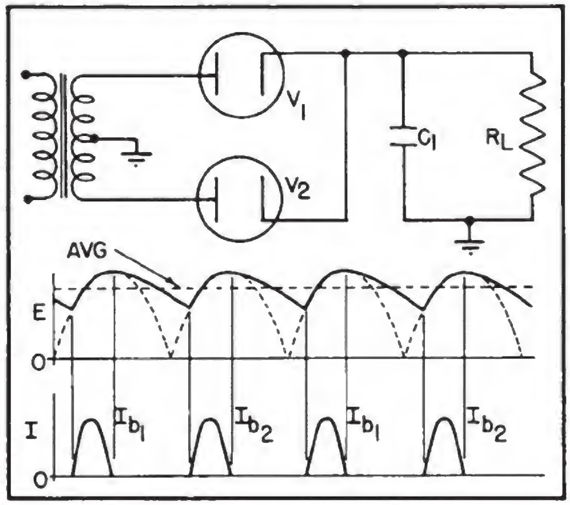

Figure 17-7 - Full wave rectifier - low resistance load.

Q7. How could the dc output voltage of the circuit illustrated in Figure 17-7 be raised to a level that equals that of the rectifier circuit illustrated in Figure 17-6.

Any filter configuration which uses a capacitor directly in parallel with the rectifier is termed a capacitive input filter. All capacitive input filters have the following characteristics.

1. High voltage output - since the input capacitor can charge to almost peak input voltage, a properly designed capacitive input filter will provide a high output voltage in comparison to the other types of filters.
2. Low current output - capacitive input filters are primarily used in low current applications. This is because peak I_b increases as R_L decreases. Peak I_b must be lower than the peak current rating of the rectifier.
3. Poor regulation - in comparison to other types of filters, capacitive input filters will have a greater change in output voltage from no load to full load conditions. Regulation is discussed in another part of this chapter.

17-4. Inductance Filter

An inductor may also be used as a filter component because of its ability to store energy in the form of a magnetic field. Because an inductor resists changes in the magnitude of current flow, it will be placed in series with the rectifier and the load rather than in parallel. Since the inductor used in rectifier filter cir-

cuits "chokes" or stops the passage of ripple into the load it is called a FILTER CHOKE.

Consider the action of a large inductor in series with the output of a half-wave rectifier. Any change in the current through the coil, either an increase or decrease, is opposed by the inductor thus affecting the voltage output as shown in Figure 17-8. The ripple has been reduced but the output is not good enough for most practical applications.

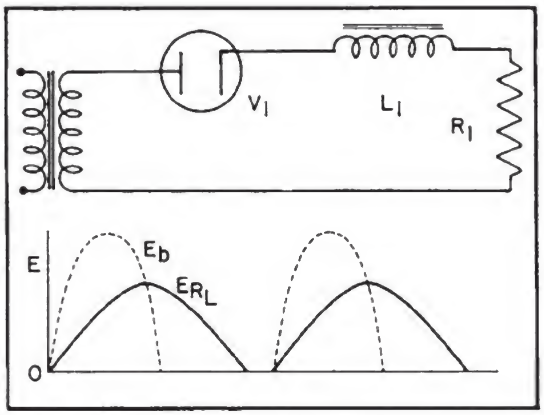

Figure 17-8 - Half wave rectifier, inductance filter.

If the same high inductance coil is placed in series with the output of a full wave rectifier a more useful output is obtained as indicated in Figure 17-9.

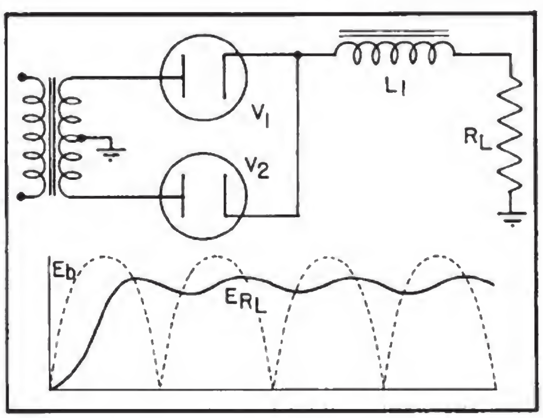

Figure 17-9 - Full wave rectifier, inductance filter.

The amplitude of the ripple voltage is determined by the ratio of X_L to R, since the inductor and the load resistor in series form an ac voltage divider. By using an inductor that has a very high inductance, a large percentage of the ac component of a rectifier's output will appear across the inductor and the ripple voltage at the output will be reduced.

The inductance prevents the current from reaching the peak value that is reached without the inductance. Consequently the output voltage never reaches the peak value of the applied sine wave. Thus, a rectifier whose output is filtered by an inductor cannot produce as high a voltage output for a given input as can one whose output is filtered by a capacitor. However, this disadvantage is partly compensated for by the fact that the inductance filter permits a larger current drain without a serious change in output voltage.

Q8. How would the plate currents (I_b) of Figure 17-8 and 17-9 compare with the output voltages?

Q9. It is desired to use a single inductor as a filter. If cost were no concern could maximum filtering be obtained by using an inductor having a core with a large cross-sectional area or using an inductor of equal value having many turns of wire. Explain.

Any filter configuration which uses an inductor directly in series with the rectifier is termed a choke input filter. Compared to capacitive input filters, inductive input filters will have the following characteristics:

1. Lower output voltage - in a full wave circuit the dc output cannot exceed the average value of the input.

2. Higher current output - this is due to the lower peak current and higher average current of the rectifier.

3. Better regulation - less change between no-load and full-load voltages.

17-5. L Type Filter

The ripple voltage present in a rectifier output cannot be adequately reduced in many cases by either the simple capacitance or inductance filter. Much more effective filtration results if both capacitors and inductors are used. The L type filter, so named because of its resemblance to an inverted L, is a filter that combines the action of a capacitor and that of an inductor to produce a voltage with a nearly constant magnitude.

Figure 17-10 illustrates the L type filter. The inductor L is directly in series with the rectifier. Therefore, the filter is classified as a choke input filter. Since the inductor is in series with the rectifier and the transformer winding, the reactance of the coil affects the charge time of the capacitor. The charge time of C1 is longer than it would be if the same

A6. The average output voltage is increased. The amplitude of the ripple voltage is decreased.

A7. Increase the capacitance of C_1.

A8. The plate currents would rise and fall in the same manner as the individual load voltages. The magnitude is dependent upon the value of components used.

A9. Using an inductor having a core with a large cross-sectional area. Increasing the turns of wire would decrease the ratio between X_L and R.

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capacitor were used in a circuit with no inductor (simple capacitance filter). This action of the input choke allows a continuous flow of current from the rectifiers. Because of the uniform flow of current the L type has applications where high currents are required.

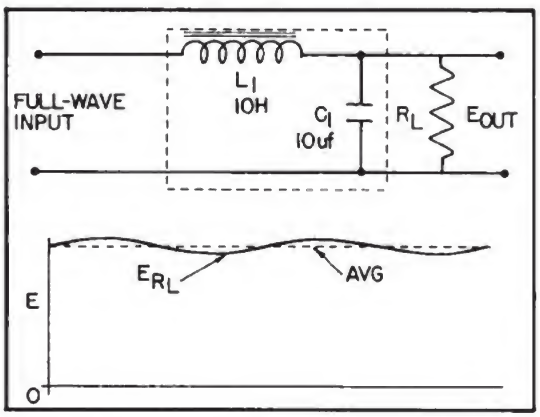

Figure 17-10 - L type filter.

As was the case with the simple inductance filter, the L type filter acts as a voltage divider. Since the L type filter network is quite frequently used, a mathematical analysis will be made of the filtering action provided by this type filter.

The unfiltered output of a full-wave rectifier resembles a series of sinusoidal alternations all of one polarity. Since it is known that the average value of one alternation is 0.637 E_{peak}, it is easily seen that the average value of the unfiltered output of a full wave rectifier is also 0.637 E_{peak}. If the peak voltage were 100 volts, the average voltage would be 63.7 volts and the ripple voltage would be 30 volts RMS. The percentage of ripple in such a case would be 47.1 percent. The effect of the L type filter may be seen by impressing the ripple voltage across the filter shown in Figure 17-11, which is merely a rearrangement of the filter shown in Figure 17-10.

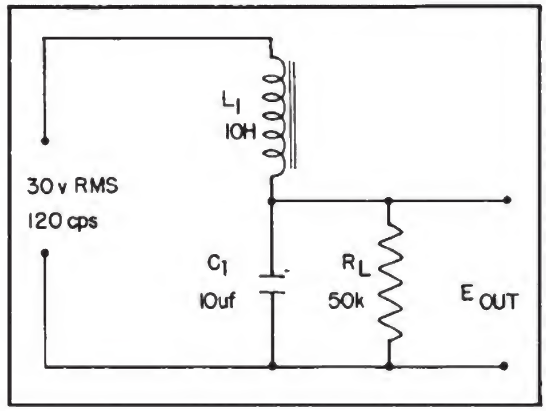

Figure 17-11 - L type filter - equivalent circuit.

Since the ratio of R_L/X_C is high, the impedance of R_L and X_C in parallel is almost equal to X_C. Consequently, R_L will be ignored in computing the total impedance.

If $f = 120$ cps

then $X_L = 7,546$ ohms

and $X_C = 132$ ohms

The impedance of L_1 and C_1 in series can now be found. Impedance ($Z = X_L - X_C$) = 7,408 ohms. The ac current ($I = \frac{E}{Z} = \frac{30}{7,408} = 4.04$ ma. Therefore E_C which is the ripple voltage is equal to (IX_C) or 0.533 volts. Percentage of ripple equals $\frac{0.533V}{63.7V}$ or 0.8% (The value of 63.7 volts dc can only be used if the dc resistance of L is considered as 0).

The percentage of ripple has been reduced from 47.1% to 0.8% by the addition of a single-section L type filter. A further reduction in ripple may be accomplished by adding more filter sections.

Q10. If the ratio of X_L to R in the circuit of Figure 17-11 is decreased, how is the output voltage affected?

17-6. Pi-Type Filter

A pi-type filter is basically a capacitor filter and an L type filter connected in parallel. Its name is derived from its resemblance to the Greek letter Pi. The circuit of Figure 17-12 is a pi-type filter.

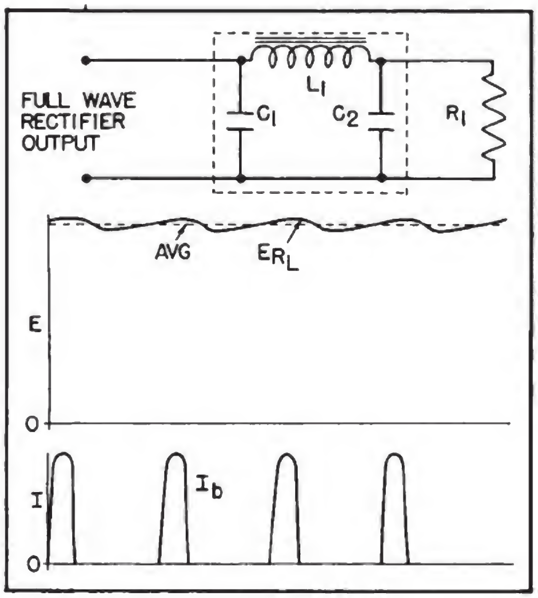

Figure 17-12 - Pi-type filter.

With this filter the output waveform closely approximates a pure dc.

The first (input) capacitor C_1 represents a low-impedance path through which most of the ripple current flows. Since the X_C of C_1 is low, very little ripple voltage appears across C_1. Most of the filtering action is accomplished by this first component. The remaining ripple voltage may be considered as appearing across L_1 and C_2 which are in series. The remaining ripple current may now flow through two possible paths, C_2 and L_1 of R_L and L_1. Since the value of R_L is quite large as compared with the X_C of C_2, almost all of the current will flow through the C_2-L_1 path. Because the X_L of L_1 is so much larger than the X_C of C_2, almost all of the remaining ripple voltage appears across L_1 and consequently does not appear in the output.

Since the large ripple current flowing through C_1 causes a fairly large voltage drop across the rectifier tube, the current flow through the tube is a series of sharp-peaked pulses. If these pulses exceed the peak current rating of the tube damage may result. Because of this, the pi-type filter is used only in low-current installations such as radio receivers.

The filtering action provided by the pi-type filter can be seen in the following mathematical analysis. First consider the output of the circuit shown in Figure 17-13A, with a simple capacitance filter.

The average dc output is 100V. The ripple amplitude is 28.2V peak to peak. The RMS value can be found by:ERMS - 0.707 E_{peak} = .707 (14.1) = 10V. The percentage of ripple then equals 10V/100V or 10%. By adding L_1 and C_2 to the circuit as in Figure 17-13B, the

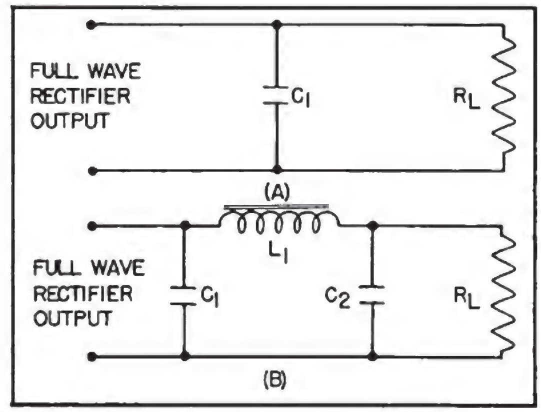

Figure 17-13 - Simple capacitive and pi-type filter.

ripple may be reduced further. The equivalent circuit appears in Figure 17-14. The values are: L_1 = 10 henrys, C_1 and C_2 = 10 MFD, R_L = 50K.

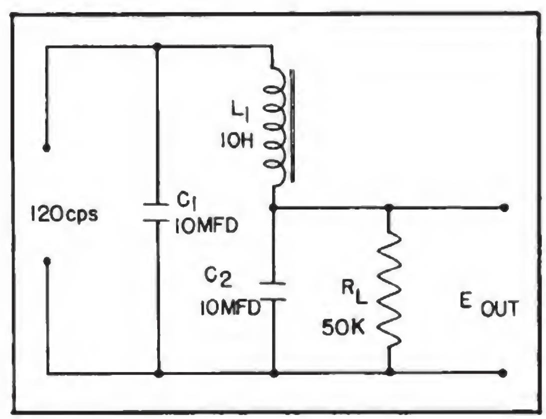

Figure 17-14 - Pi-type filter, equivalent circuit.

The reactances can now be found:

$$X_C = \frac{0.159}{fc} = \frac{159(10^{-3})}{120(10))10^{-6})} = 132 \text{ ohms}$$

$$X_L = 2\pi f L = 6.28(120)\ 10 = 7540 \text{ ohms}$$

L_1 and C_2 act as a series ac voltage divider. We can disregard R_L since its value is well

A10. The average dc voltage is decreased and the percentage of ripple is increased.

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above ten times greater than X_C. The ac voltage drop across C_2 is the new ripple value since R_L is in parallel with C_2. We can find the ac component of current flow through the branch composed of L_1 and C_2 by the following method:

$$Z = X_1 - X_C = 7,408 \text{ ohms}$$

$$I = E/Z = 10/7,408 = 1.35 \text{ ma}$$

Since the ac voltage drop across C_2 is equal to the ripple:

$$E_C = IX_C = 1.35 \text{ ma}(132) = 0.18 \text{ vac}$$

The new percentage of ripple will equal 0.18/100 = 0.18%.

In many cases where cost and size are a factor L may be replaced with a resistor. The value of resistance used, however, will be a compromise between good filtering and high dc output. The reactance of L is high while the dc resistance is low. This means the ac (ripple) voltage drop across L_1 will be large while the dc voltage drop will be low. If the value of R was equal to the X_L of L_1, percentage of ripple would remain low but the dc output would be reduced due to the large IR drop across the resistor. If the value of R was equal to the dc resistance of L, the dc output would remain high, but the percentage of ripple would increase due to the change in R/X_C ratio (formerly the X_L/X_C ratio).

Q11. Refer to the capacitive input filter of Figure 17-14. Which capacitor requires the most critical peak voltage rating. Explain.

REGULATION

17-7. Percentage of Regulation

When a load is placed on a power supply, the terminal voltage generally decreases. The comparison of this fall of voltage to the full-load voltage, expressed in percent, is called regulation. A circuit has poor regulation if a large drop occurs in the terminal voltage when full load is applied.

The formula for the percentage of regulation is:

$$\%R = \frac{E_{NL} - E_{FL}}{E_{FL}} \times 100 \qquad (17\text{-}2)$$

where E_{NL} is the no-load voltage, and E_{FL} is the output voltage when full-load current is flowing. For example, assume the no-load voltage of a certain power supply to be 300 volts and the voltage at the output terminals to be 250 volts when the full rated load current is drawn from the power supply. Substituting these values in this formula gives percentage of voltage regulation:

$$\%R = \frac{300-250}{250} \times 100 = 20 \text{ percent}$$

The difference between the no-load voltage and the full-load voltage is caused by the flow of load current through the internal resistance of the power supply. The IR drop caused by the load current within the supply circuit is subtracted from the voltage available for the load resistance at the output terminals. A perfect power supply would have zero internal resistance and the percentage of regulation would be zero. Such a supply would provide the same voltage under full-load that it develops with no-load current flowing. In general, the lower the percentage of regulation, the better is the power supply in furnishing dc voltage and current for electronic equipment.

17-8. Regulation of a Capacitor-Input Filter

A capacitor-input filter with no load produces a termimal voltage which is nearly equal to the peak value of the applied alternating voltage. As the load is increased, the terminal voltage falls, because the current drawn by the load prevents the capacitor from retaining its charge. The capacitor-input filter is undesirable for applications which require a large current, because the peak current that must flow in the tubes to charge the input capacitor may damage the tubes or require the use of large, expensive tubes. Since the output voltage falls considerable as the load current is increased, this type of filter is said to have relatively poor regulation (see Figure 17-15). It may be used, however, where the load is light or absolutely constant.

17-9. Regulation of Choke Input Filter

The regulation of choke input filters will be discussed by considering a specific type of filter, the L type. At no load the output voltage of the choke input filter is nearly equal to the peak voltage of the sine wave applied. This high voltage can be obtained because with no load current being drawn the capacitor can be charged to the peak voltage. However, if only a small load current is drawn, the output voltage falls sharply to some lower value. (See Figure 17-15). As the load current increases

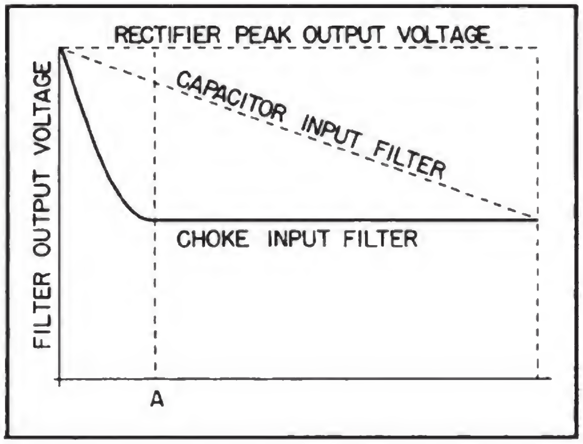

Figure 17-15 - Effect of load on terminal voltage of capacitor and choke input filters.

beyond a value indicated by point A in the illustration, there is very little change in voltage except that which takes place in the dc resistance of the choke coil.

Since the voltage at the output of a choke input filter changes very little over a wide range of load, a choke filter has good regulation. In practice, a fixed minimum load which will draw a current of the magnitude A, usually is put across the terminals of the filter to prevent the large change of voltage which takes place between no load and the load at point A.

Q12. Which has the lowest percentage of regulation, a capacitor input filter or a choke input filter?

17-10. Voltage Dividers

A resistor in many cases is placed across the output terminals of a rectifier power supply. The name applied to such a resistor depends on its principal use. If it serves the purpose of bleeding off the charge on the filter capacitors when the rectifier is turned off, the resistor is called a BLEEDER RESISTOR. If it serves the purpose of applying a fixed minumum load to a filter circuit to improve the voltage regulation of the power supply, it is called a minimum LOAD RESISTOR. If loads are connected to the resistor at various points to provide a variety of voltages which are less than the terminal voltage, the resistor is called a VOLTAGE DIVIDER.

In general a resistor placed across the output terminals of a rectifier power supply may fulfill all of these functions. However, if the resistor is to be a bleeder resistor only, it can have a very high resistance so that it will draw a negligible current from the rectifier. If the resistor is to serve as a minimum load resistor, it should be of such a value that it will draw approximately 10 percent of the full load current. It must be of sufficient wattage rating to dissipate the heat produced by the current flowing through it while the circuit is energized.

17-11. Circuits

A resistor which is used as a minumum load resistor also may be used as a voltage divider because the current flowing through the resistor produces a voltage drop across it equal to the impressed voltage. In Figure 17-16, three similar resistors are connected in series

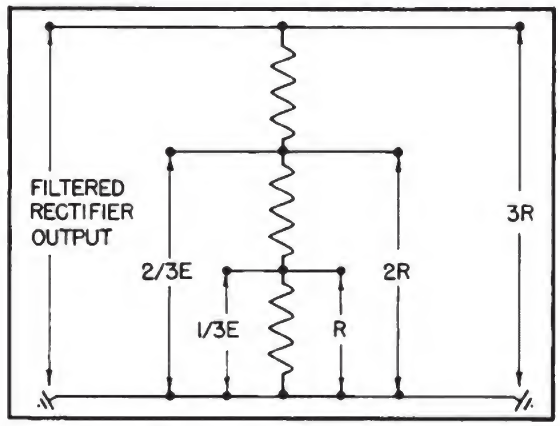

Figure 17-16.- Simple voltage divider.

As long as no load is drawn from any terminal except the top or line terminal, the voltage across the resistors will divide proportionally to the resistance of each as shown.

It is common practice to ground one side of most circuits. Therefore ground potential is normally used as a reference for measurement of voltages as at point D of Figure 17-17(1). If a rectifier and its filter are connected so that no parts of the power supply are grounded, it is possible to ground the circuit at any point without affecting the operation of the rectifier, providing the insulation of all parts is sufficient to withstand the voltage involved. Thus in Figure 17-17(2), point C is grounded and point D becomes negative with respect to ground. Such a circuit is frequently used to furnish both plate and bias voltages from the same power supply. In Figure 17-17(3), point A is grounded and all voltages along the divider are negative with respect to ground. An important point to note, however, is that point A will always be MORE POSITIVE than point B so long as the power supply polarity is maintained as shown in the figures.

It has been assumed in Figure 17-16 and 17-17 that no load was attached to the divider

A11. The capacitor C_1. At the beginning of charging it will charge to the peak value of the input.

A12. The choke input filter.

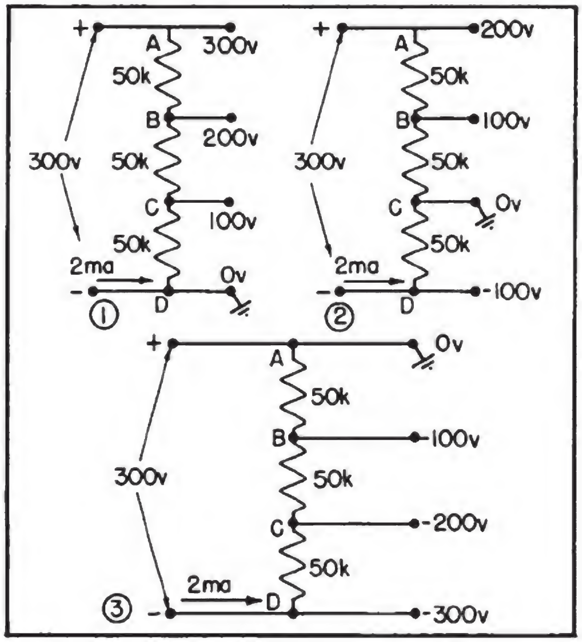

Figure 17-17 - Effect of moving ground point on a voltage divider.

except across the line terminals A and D and that voltages could be measured without drawing appreciable current. As soon as a load is attached to the divider at any intermediate terminals, the voltage division shown no longer is correct. This is because the resistance of the attached load forms a parallel circuit with the part of the divider across which it is placed, and therefore changes the total resistance between the terminals concerned.

For example, in Figure 17-18, a load of 150,000 ohms (150K) is placed across BD and a load of 50,000 ohms (50K) across CD. The resistance between C and D is first determined by Ohm's law for parallel resistance, or

$$R_{cd} = \frac{50K \times 50K}{50K + 50K} = 25K$$

To this is added the series resistance of the middle divider resistor: 25K + 50K = 75K. The resistance across BD is then found by the parallel resistance rule, or

$$R_{bd} = \frac{75K \times 150K}{75K + 150K} = 50K$$

The total resistance between A and D is then this resistance of 50K plus the resistance of the first divider resistor, or: 50K + 50K = 100K. The total current taken by the divider and its two loads is then the available voltage divided by this resistance, or:

$$I = \frac{300V}{100K} = 3 \text{ milliamperes}$$

This current of 3 milliamperes flowing in the first divider resistor, R_1, produces an IR drop of 50K x 3 milliamperes = 150 volts. Therefore, when loads No. 1 and No. 2 have the values as shown, this first resistor absorbs one-half of the available voltage instead of one-third as in the no-load condition of Figure 17-17. The 3 milliampere current at point B is the sum of the currents through R_2 and load No. 1. Across load No. 1 there is: 300 volts minus 150 volts equals 150 volts. Then the current through load No. 1 is $\frac{150V}{150K}$ = 1 milliampere and the current through R_2 is 3 milliamperes minus 1 milliamperes = 2 milliamperes. The 2 milliamperes flowing in R_2 again produces an IR drop which is 50K x 2 milliamperes = 100 volts. Thus the voltage between points C and D must be 150 volts minus 100 volts = 50 volts. The current flowing in load No. 2 is then $\frac{50V}{50K}$ = 1 milliampere, leaving 1 milliampere of current through R_3. As a check the IR drop across R_3 can be found. 50K x 1 milliampere = 50 volts. Since this is the same voltage previously determined across CD, the value of current must have been correct.

Instead of a voltage of 200 volts at B and 100 volts at C as in Figure 17-17(1), the voltage is now 150 volts at B and 50 volts at C with the loads connected as shown in Figure 17-18. Other values of loads will give correspondingly different values of voltage at B and C. Thus it can be seen that the voltage appearing across the intermediate terminals of a voltage divider will divide proportionately to the values of the divider resistors only as long as no appreciable load drawn is from these terminals. Under loaded conditions the voltages at these terminals will have various values, depending upon the resistance of the loads. A voltage divider must therefore be designed for the particular load conditions under which it is to operate.

Q13. R_2 of Figure 17-18 becomes open. What is the output voltage across the main load?

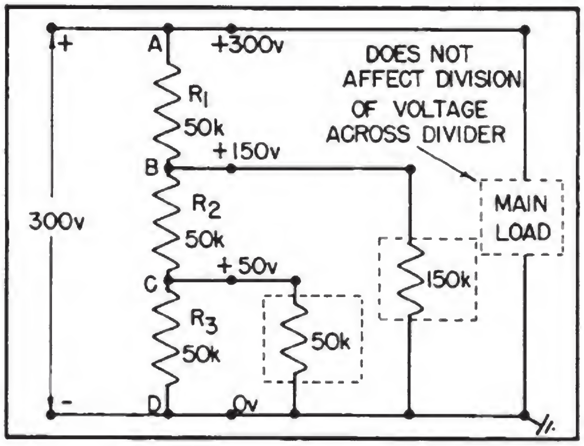

Figure 17-18 - Effect of loads on voltage division.

Q14. With R_2 of Figure 17-18 open, what is the effect upon the current drawn from the supply?

Q15. Under the same condition as stated in Question 13 and 14, what is the effect upon the current through the main load?

A13. 300 volts.

A14. Decreases.

A15. Remains the same.

EXERCISE 17

1. What purpose does a filter serve when used as a part of a power supply?
2. What is meant by the term ripple voltage?
3. A half-wave rectifier has an input frequency of 60 cycles. What is its ripple frequency?
4. A full-wave rectifier has an input frequency of 60 cycles. What is its ripple frequency?
5. What is the percentage of ripple of a power supply which has an average dc output of 150 volts and a peak ripple output of 5 volts?
6. Describe how the amplitude of a rectifier's output voltage having a capacitance filter is affected by the input frequency.
7. A rectifier having a capacitance filter has a large resistive load. Compare the charge time of the capacitor to its discharge time.
8. What is the average voltage of an unfiltered full-wave rectifier?
9. How is the average dc output voltage that is taken off a capacitance filter affected by an increase in the load resistance?
10. How is the output of a rectifier circuit having a simple inductance filter affected by an increase in load current?
11. How is the output of a rectifier circuit having a simple inductance filter affected by an increase in load resistance?
12. How is the output voltage of a power supply with a simple inductance filter affected if it is converted to an L type filter.
13. The output of an unfiltered circuit having a capacitance filter has an average dc output of 150 volts and a percentage of ripple of 5%. If this output is applied to an L section filter having an inductance of 10 henrys and a capacitance of 10 microfarads what is the new percentage of ripple?
14. How does the output voltage of an L type filter compare with a simple inductance filter (the value of the inductance and the load are equal).
15. If the inductor of a pi-type filter is replaced with a resistor what is the effect on the output voltage?
16. What is meant by the term regulation when applied to a power supply?
17. Compare the regulation of a choke input filter to a capacitance input filter.
18. What is the purpose of a bleeder resistor?
19. How does a bleeder resistor affect the regulation of a choke input filter?
20. A power supply has an output voltage of 200 volts under a no-load condition. If this output drops to a value of 150 volts when its full rated load is connected, what is the percentage of regulation?
21. What purpose is served by a voltage divider?

CHAPTER 18

REGULATOR CIRCUITS

In this chapter, the basic concept of gas filled regulating tubes will be presented. A need for voltage regulation will be considered, as well as methods of regulating voltage. The physical and electrical characteristics of voltage regulating gas-filled tubes will be explained. Finally, basic voltage regulating tube circuits will be discussed.

18-1. The Need for Voltage Regulation

Due to their internal construction, all devices used to supply dc power to a load have internal resistance. If current varies through this internal resistance, the output voltage will also vary. Typical devices used to supply dc power to a load are batteries, dc generators and electronic power supplies.

Figure 18-1 shows a battery with internal resistance connected to a variable load resistance. The details of this circuit were considered in Chapter 6 and will be reviewed briefly at this time.

If R_L (Figure 18-1) decreases, the circuit current increases causing an increased voltage drop across the internal resistance of the battery. This, in turn, results in reduced voltage (E_t) to the load resistance. Conversely if R_L increases in resistance, E_t increases. It would be desirable to have no internal resistance within the battery, resulting in a constant voltage across the load regardless of current variations. This, however, is not possible, since all practical devices used to produce dc power have internal resistance.

Due to the resistance of the wire used in the construction of dc generators, such devices also have internal resistance. The effects of current variations through this internal resistance are the same as those explained for a battery circuit.

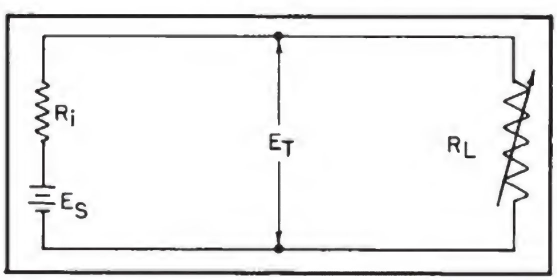

Figure 18-1 - Effects of changing load on battery voltage.

An electronic power supply has internal resistance which is a combination of the diode tube resistance, transformer secondary winding resistance, and resistance within the filter choke. Again, variations in current through this internal resistance will result in changes of voltage at the output of the power supply.

The output voltage of a power supply is also dependent on the amount of input voltage to the power supply. Since neither changes in the output voltage, nor internal power supply resistance can be eliminated, some means of reducing their effects is desirable. A nearly constant output voltage can be achieved through the use of either a series or a shunt voltage regulator.

Q1. Does the internal resistance of a power supply affect output voltage if power supply current varies?

METHODS OF VOLTAGE REGULATION

Two methods used to provide a regulated or constant voltage across the load will be discussed in this chapter. One means of accomplishing voltage regulation can be illustrated by a variable resistor connected in series with the load. This method of voltage regulation is called SERIES REGULATION. The other method to be discussed can be illustrated by a variable resistor in parallel with the load. This method of voltage regulation is called SHUNT REGULATION.

18-2. Series Regulation

Figure 18-2 is a schematic diagram of a basic series regulator.

Since the series regulator compensates for variations in either line voltage or load resistance, its discussion will be considered in two

A1. Yes. Since the voltage drop across internal resistance subtracts from output voltage.

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steps. Figure 18-2 will be used to explain series regulation for variations in line voltage while Figure 18-3 will show regulation as load resistance varies.

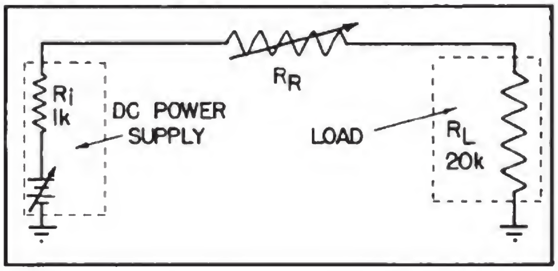

Figure 18-2 - Effects of varying line voltage.

In Figure 18-2, the dc power supply has been replaced by a variable battery having internal resistance. R_L represents a constant load resistance, R_R the series regulating resistance and R_i the internal resistance of the power supply.

In Figure 18-2 it is desired to have a constant 80V across the load resistance. With 100V produced by the battery, 80V will appear across the load if R_R has a resistive value of 4K ohms. Since R_L is considered constant, to maintain 80V across it, a current of 4 ma must flow through the load.

If the battery produces 110V, R_R must be increased to 6.5K ohms to limit the current to 4 ma through the load resistance. Under this condition 80V is still applied to the load resistance. It can be seen in this case that R_R provides voltage regulation by maintaining a constant current through the load.

In Figure 18-3, the dc power supply is shown as a constant potential battery having internal resistance. R_R is the series regulating resistor and R_L is shown as a variable load resistance. In this circuit. R_R will compensate for variations in load resistance.

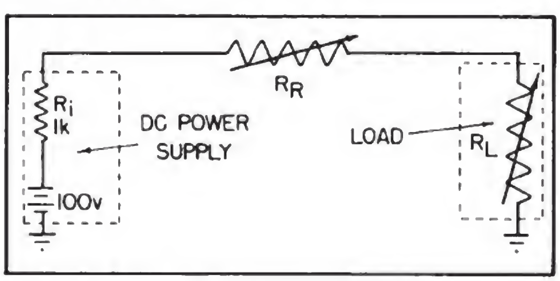

Figure 18-3 - Effects of varying load resistance.

With a load resistance of 20K ohms, the constant potential of 100V developed by the battery will cause 80V to be felt across the load if R_R has a value of 4K ohms. If R_L were to decrease to 10K ohms, R_R must decrease its value to 1.5K ohms to maintain 80V across the load. To arrive at these values, first consider the change in load resistance. With a new value of 10K ohms, the current through R_L must be 8 ma to obtain an 80V potential across the load resistance. Since this is a series circuit, 8 ma will be the total current in the circuit. With a total voltage of 100V, total resistance is found to be 12.5K ohms. The value of R_i and R_L are known, leaving only R_R to be computed. Since resistance is additive in a series circuit. R_R is found by subtracting the sum of R_L and R_i from total resistance. This gives a value of 1.5K ohms for R_R. Through the use of a variable series resistance, a constant potential has been maintained despite variations in load resistance.

Q2. If line voltage were to decrease, how must R_R be varied to maintain a constant load voltage?

Q3. If the load resistance were to increase, how must R_R be varied to maintain a constant load voltage?

18-3. Shunt Regulation

The shunt regulator compensates for changes in line voltage and changes in load resistance. Each of these will be considered separately using Figure 18-4. and 18-5. Notice that the regulating resistor R_R is now placed in parallel (shunt) with the load resistance.

In Figure 18-4, the dc power supply is shown as a variable battery having a constant internal resistance (R_i). The resistance of the load (R_L) is considered constant while R_R is the regulating shunt resistance.

In Figure 18-4 it is desired to have a constant 80V potential across the load resistance. If the battery potential is 100V, R_R must have a value of 5K ohms to cause the internal resistance of the battery (R_i) to drop 20V. To develop

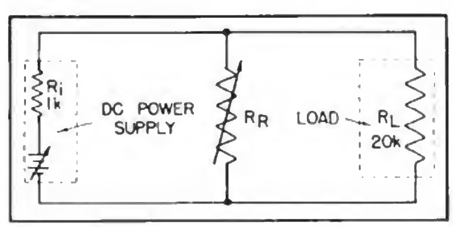

Figure 18-4 - Effects of varying line voltage.

20V, R_i must have 20 ma flowing through it. R_L needs only 4 ma to produce an 80V drop. The remaining 16 ma flows through shunt resistor R_R. To develop 80V, at 16 ma, R_R has a value of 5K ohms.

Should the battery potential increase to 110V the internal battery resistance must now drop 30V, leaving 80V across the parallel circuit composed of R_L and R_R. To develop a 30V drop, R_i must have 30 ma flowing through it. Since R_L needs only 4 ma to develop 80V, the additional 26 ma must flow through R_R. To develop an 80V drop at 26 ma, R_R must be decreased to a value of approximately 3.08K ohms.

In Figure 18-5 the dc power supply is represented as a constant potential battery having an internal resistance (R_i). The load resistance is shown as the variable resistance (R_L) and the shunt regulating resistance as (R_R).

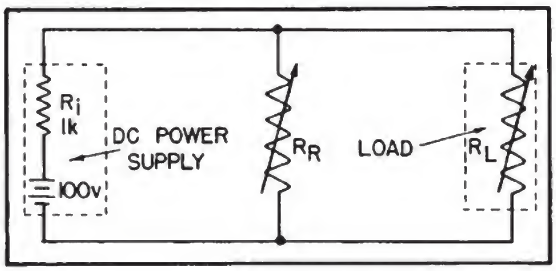

Figure 18-5 - Effects of varying load resistance.

If R_L has a value of 20K ohms and the battery produces 100V, 20V must be dropped by the battery's internal resistance, R_i. This requires a total current of 20 ma. For an 80V drop to be developed across R_L, 4 ma must flow through it. The remaining 16 ma flows through shunt resistor R_R. To develop 80V at 16 ma, R_R must have a resistance of 5K ohms.

If the resistance of R_L decreases to 10K ohms 8 ma will be required through the load to develop an 80V drop across it. Since total current required is still 20 ma (applied voltage is remaining constant), only 12 ma needs to flow through R_R. To develop 80V at 12 ma, R_R must increase in resistance to approximately 6.67K ohms. It should be noticed that, in the case where load resistance changes, the effect of shunt R_R is to maintain a constant total resistance in the circuit.

The foregoing explanation shows that a variable resistor placed either in series or in shunt with a load resistance can compensate for changes in line voltage as well as load resistance changes. Such a circuit would prove of little practical value since R_R must be controlled manually. Manual operation of the regulating resistor would be too slow to compensate for rapid changes which might affect load voltage. For this reason, electronic regulating devices are used. Acting as variable resistances, these devices can operate automatically, thereby compensating for rapid changes which would affect load voltage.

Q4. If line voltage were to decrease, what must happen to the resistance of R_R to maintain a constant load voltage?

Q5. If load resistance were to increase, what must happen to the resistance of R_R to maintain a constant voltage to the load?

GAS FILLED REGULATING TUBES

One means of overcoming the disadvantage of a variable resistor used for regulation, is to use gas filled VOLTAGE REGULATOR (VR) tubes. VR tubes have the ability to maintain a relatively constant voltage drop across them, even though current through them may be changing over a range of values. The construction and operation of gas filled regulating tubes will now be considered.

18-4. Physical Characteristics of VR Tubes

The basic construction of the VR tube is shown in Figure 18-6. The anode is a wire located at the center of the cathode. The cathode is a large cylinder which completely surrounds the anode. Attached to the cathode is a probe which extends inward toward the anode. This probe is known as the STARTING ELECTRODE and permits the tube to start conduction at a lower voltage than would be possible without the probe. Figure 18-6 also shows the schematic symbol for a VR tube. The black dot indicates that the tube is gas filled.

The anode of VR tubes is usually constructed

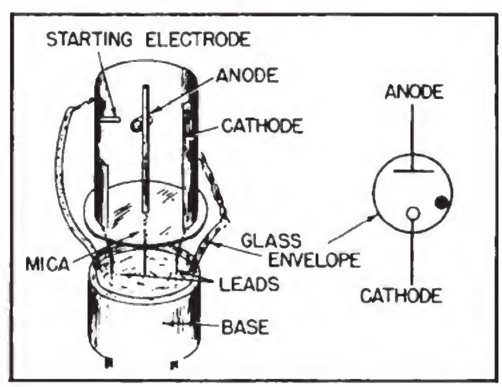

Figure 18-6 - Basic structure and symbol of VR tube.

A2. R_R decreases.

A3. R_R increases.

A4. R_R must increase.

A5. R_R must decrease.

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of nickel, and has a very small surface area compared to the cathode. Cathodes are usually constructed of nickel with an oxide coating on the inside surface. Gases commonly used in such tubes are of the inert variety such as argon, helium, neon or combinations of these. These gases are placed within the tube under relatively low pressure. The entire structure is contained within a glass envelope with conductive leads from the electrodes to respective base pins. Physical support for the electrodes is provided by mica or some other non-conductive material.

In Figure 18-7, base diagrams are shown for typical VR tubes. Notice in Figure 18-7B, a shorting wire is shown between pins 3 and 7. This is referred to as the JUMPER and provides a means of disconnecting power when the VR tube is removed from the circuit.

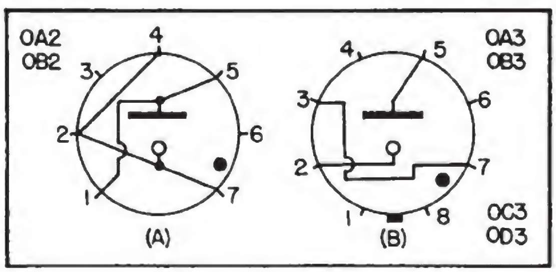

Figure 18-7 - VR tube pin connections and numbers.

It should be noted from the previous diagrams that VR tubes have no heating element. Such tubes are referred to as COLD CATHODE type tubes. Although the tube has two elements and can be called a diode, its physical construction is considerably different from the high-vacuum diode. These factors give the VR tube electrical characteristics completely different from the high-vacuum diode.

Q6. How do VR tubes differ physically from high-vacuum diodes?

18-5. Electrical Characteristics of VR Tubes

The electronic operation of a typical VR tube will be explained using the volt-ampere curve illustrated in Figure 18-8A.

With no plate voltage applied to the VR tube a small number of free electrons exist in the space between plate and cathode. These electrons are produced by light energy and other forms of radiation which cause a small number of the gas molecules to become ionized.

If a positive potential is applied to the plate, the free electrons will be attracted to the plate forming a minute flow of plate current (commonly less than one microamp). As the plate voltage is increased more and more of these free electrons are attracted to the plate. At point A, the electrons are attracted to the plate as rapidly as they are produced by ionization. Thus, as the plate voltage is increased from 0 to X, plate current will increase from 0 to A. Since the small degree of ionization existing at this time is not sufficient to produce a visible amount of light, this current is called DARK CURRENT.

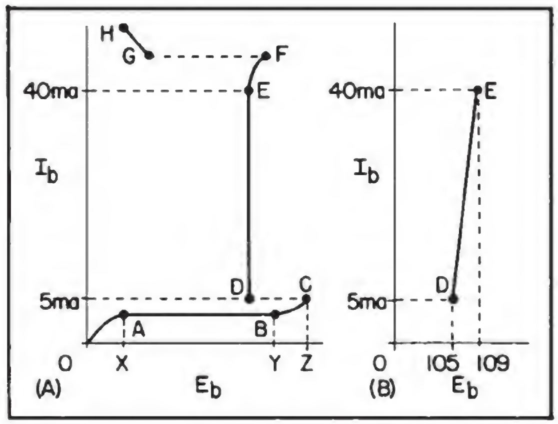

Figure 18-8 - Volt-ampere curve for a typical VR tube.

As the plate voltage is increased from X to Y no additional current can be obtained. This region of the curve (from A to B) is called DARK CURRENT SATURATION.

Although no increase in current occurs from A to B, the velocity of the few available electrons increases steadily as the plate voltage is increased from X to Y. At a plate voltage corresponding to point B, the velocity of the electrons travelling to the plate becomes great enough to knock electrons from some of the gas atoms with which they collide. These electrons are also attracted to the plate causing a rise in plate current. This is indicated by the upward rise in the curve between points B and C.

The positive ions generated by the electron collisions are attracted to the negative cathode. Upon striking the cathode the kinetic energy of the heavy positive ions is converted to thermal energy causing the cathode to become heated. Thus, the positive ions produce thermionic

emission from the cathode, along with a significant amount of secondary emission (due to ionic bombardment).

The new electrons thus liberated are attracted to the plate, in turn causing additional ionization. As the plate voltage is increased from Y to Z the ionization and emission rise at an ever increasing rate, until at point C a sudden avalanche of current occurs (current surges from one microamp to several milliamps) causing a marked decrease in the internal resistance of the tube. The drop in resistance causes a sharp reduction in voltage drop across the tube shifting the operation to point D.

As the avalanche of current occurs between points C and D, the area between cathode and plate suddenly begins to glow as a result of the heavy recombination of ions and electrons. Due to the characteristic sudden appearance of light within the tube, the plate voltage at which avalanche occurs is called the FIRING POTENTIAL, STRIKING POTENTIAL, or IONIZATION POTENTIAL.

The firing potential depends mainly on electrode spacing, type of gas, gas pressure, and gas temperature. For a given VR tube the firing potential is fixed, being determined by the design of the tube.

Between points D and E the curve is nearly vertical, indicating that the degree of ionization (and therefore the internal resistance) is extremely sensitive to small changes in plate voltage. Using the magnified view of the curve from D to E shown in Figure 18-8B, it can be seen that a slight increase in plate voltage from 105 to 109 volts is sufficient to produce an increase of from 5 to 40 ma of plate current. IT IS IN THIS AREA OF THE CURVE THAT THE VR TUBE ACTS AS A VARIABLE RESISTANCE AND CAN BE USED AS A VOLTAGE REGULATING DEVICE.

At a plate voltage corresponding to point E the internal glow completely covers the cathode. Beyond point E the glow intensifies causing multiple ionization and severe ionic bombardment of the cathode. If allowed to continue, operation over this section of the curve results in excessive heating of the cathode and eventual destruction of the tube. This region is called the abnormal glow region.

At point F an arc discharge occurs at which time the internal resistance of the tube drops to an extremely small value. The section of the curve from G to H is called the arc discharge region and exhibits a negative resistance characteristic. Although VR tubes are destroyed by operation in this region, certain tubes are designed to operate over this portion of the gas discharge curve. Examples of these tubes are mercury vapor rectifiers and three element gas tubes called thyratrons.

If after operation has begun, current drops below 5 ma, DE-IONIZATION will occur. The potential at which de-ionization occurs is called DE-IONIZATION POTENTIAL or the EXTINCTION POTENTIAL.

Table 18-1 gives characteristics of common VR tubes. This table includes a column that shows the amount of regulation to be expected over the operating range of the tube.

Type	Operating Volts	Current Min.	Current Max.	Minimum Supply	Reg V.
OA2	150	5	30	185	2
OA3-VR75	75	5	40	105	5
OB2	108	5	30	133	2
OB3-VR90	90	5	40	130	6
OC2	75	5	30	105	5
OC3-VR105	105	5	40	135	2
OD3-VR150	150	5	40	185	4
OG3	85	1	10	125	4
1B46	80	1	2	225	3

Table 18-1 - Voltage regulator tube ratings.

As can be seen from the above table, a variety of VR tubes are available. A common designation for VR tubes is by use of a number such as VR105-40. The letters indicate the function of the tube (voltage regulator). The numbers preceding the dash indicates the regulated voltage while the number following the dash indicates the maximum current (in milli-amperes) allowed and still maintain regulation.

The minimum supply voltage column indicates the lowest supply voltage which will insure firing each time the supply is energized.

The minimum value of current given in the table is the current required to sustain operation within the normal glow discharge region. This current is sometimes called the "keep alive" current.

Although VR tubes regulate within a range of one to seven percent, this degree of regulation may not be sufficient for certain electronic circuits. A second disadvantage in the use of VR tubes is the inability to vary regulated voltage over a continuous range such as would be required in a variable power supply. Under these conditions, other means are used to provide voltage regulation.

Q7. To maintain a relatively constant voltage across a VR tube, in which region must the tube be operated?

Q8. As the degree of ionization increases, what happens to the internal resistance of the VR tube?

A6. A VR tube has no heater, its cathode is larger than the anode and surrounds the anode, is gas filled, and uses a starting electrode.

A7. The normal glow discharge region.

A8. The resistance decreases.

Q9. What is the meaning of the minimum current rating of a VR tube?

VR TUBE REGULATOR CIRCUITS

In previous portions of this chapter it has been shown that a variable resistor can provide voltage regulation. Since a voltage regulator tube acts as a varying resistance within its normal operating range and provides a near constant voltage across its electrodes, it lends itself directly as a means of regulating power supply output voltages. Typical VR tube circuits will now be discussed.

18-6. Basic VR Tube Regulator Circuit

Figure 18-9 shows a basic VR tube regulating circuit. The voltage produced by the source is 150V. The VR 90-40 will provide a constant 90 volts across the load resistance (R_L) if the tube is operated in the normal glow discharge region. This means that 60 volts is dropped across R_s the series limiting resistance used to limit the current through the VR tube.

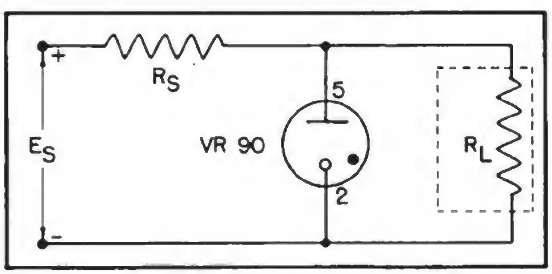

Figure 18-9 - Basic VR tube regulator

Since the operating limits of a VR tube are determined by its maximum and minimum currents, circuits using such tubes should be designed to allow maximum variations in current above and below the normal point of operation. To allow maximum variations in current, the normal point of operation must be midway between the current limits of the tube. This median current is called I_{mean} and can be calculated by the use of the following formula:

$$I_{mean} = \frac{I_{max} + I_{min}}{2} \qquad (18\text{-}1)$$

Using the circuit in Figure 18-10 the mean current for the VR90-40 would be:

$$I_{mean} = \frac{40 + 5}{2} = \frac{45}{2} = 22.5 \text{ ma}$$

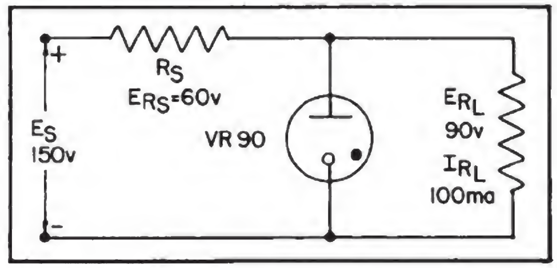

Figure 18-10 - Simplified VR tube regulator

To calculate the value of series dropping resistance R_s, the following formula should be used:

$$R_s = \frac{\text{Source Voltage - Regulated Voltage}}{I_{mean} + I_{load}\text{ (average)}} \qquad (18\text{-}2)$$

If the average current flowing through the load of Figure 18-10 is 100 ma, the series dropping resistance can be found in the following manner:

$$R_s = \frac{150 - 90}{22.5 + 100} = \frac{60 \text{ volts}}{122.5 \text{ ma}} = 490 \text{ ohms}$$

Using Ohm's law, the value of load resistance for the circuit of Figure 18-10 will be 900 ohms if a current of 100 ma flows through R_L. The internal resistance of the VR tube can be calculated in a similar manner. With 22.5 ma flowing and 90V dropped across the VR tube, its resistance is 4K ohms.

To show voltage regulation in the circuit for Figure 18-10 assume a constant supply voltage of 150V and a variable load resistance. If the value of R_L were to decrease to 857 ohms, the load current would increase to approximately 105 ma. To maintain 90V across the load resistance, R_s must drop 60V. To do so requires a current of 122.5 ma flowing through the series resistance. Since 105 ma is now flowing through the load, the current through the VR tube must decrease from 22.5 ma to 17.5 ma. To understand the manner in which tube current is made to vary, the sequence of events will be considered in more detail.

The original load resistance was 900 ohms. Changes in this resistance will not occur

instantaneously, but will require some time to vary from 900 ohms to a new value. As resistance of the load begins to decrease, load current begins to increase. This minute increase in load current will flow through the series resistance R_s causing a slight increase in ER_s. This slight increase in voltage across R_s will result in VR tube voltage dropping slightly. This slight drop in tube voltage will cause a decrease in the ionization of the tube gas which in turn increases the resistance of the tube. As a result, less current flows through the tube.

It should be noted that tube current can decrease only to a value of 5 ma before de-ionization occurs. Therefore, the load current cannot exceed 117.5 ma, for beyond this value tube current becomes less than 5 ma and regulation ceases.

If load resistance were to increase, load current would decrease. This would result in VR tube current increasing to maintain a current of 122.5 ma through R_s. The VR tube current can only increase to 40 ma. Beyond this value of current the tube enters the abnormal glow region and tube voltage increases. The upper limit of VR tube current will occur when load current decreases to a value of 82.5 ma. When load current drops below this value, the VR tube ceases to regulate the load voltage. It can be seen, therefore, that with a constant source voltage but variable load resistance, the limits of regulation will be reached when current in the load exceeds 117.5 ma or drops below 82.5 ma.

The VR tube regulator can also compensate for changes in power supply voltage. Under these conditions, the load resistance will remain constant while power supply voltage will be variable. Reference should be made to Figure 18-10 for the following discussion.

Assume the source voltage begins to increase from an original value of 150V toward 155V. As this voltage increases, current through R_s increases from its original value of 122.5 ma. Initially, this additional current is drawn from the load causing a slight increase in load voltage. This increase in load voltage is felt across the VR tube and causes an increase in tube ionization. This decreases the internal resistance of the VR tube with a resultant increase in tube current. When source voltage reaches 155V, current through R_s is approximately 133 ma (R_s = 490 ohms). Most of the additional current through R_s flows through the VR tube. As a result, approximately 33 ma flows through the VR tube maintaining load voltage at 90V.

It can be seen that as the source voltage increases the current through the VR tube increases. Since the upper limit of tube current is 40 ma, there is a limit in the ability of the tube to regulate increasing voltage. When the supply voltage exceeds 158.6V, tube current will be greater than 40 ma and regulation will cease.

If source voltage were to decrease from 150V to 145V, only 55V must be dropped across the 490 ohm series resistance to enable load voltage to be maintained at 90V. Current through R_s for a 55V drop is 112 ma. Since load current is 100 ma, the remaining 12 ma must flow through the VR tube. This represents a decrease in the ionization level of the VR tube with a resultant increase in tube resistance. Under these conditions, 90V will be maintained across the load resistance.

Since VR tube current decreases as source voltage decreases, some point will be reached where tube current drops below its lower limit of 5 ma. When source voltage drops below 141.4V tube current will be less than 5 ma and regulation will cease. The upper and lower limits of supply voltage variations which can be allowed and still provide regulation in the circuit for Figure 18-10 is 158.6V and 141.4V respectively. It should be remembered that tube voltage does vary slightly (see table 18-1) through its operating range but this voltage change is less than would exist without the use of a VR tube.

Q10. In a properly designed VR tube regulating circuit, what happens to tube resistance as supply voltage decreases?

Q11. What happens to the degree of VR tube ionization as the load resistance decreases?

18-7. VR Tubes Connected in Series

In applications where a regulated voltage in excess of the maximum rating of one tube is required, two or more tubes may be placed in series as shown in Figure 18-11.

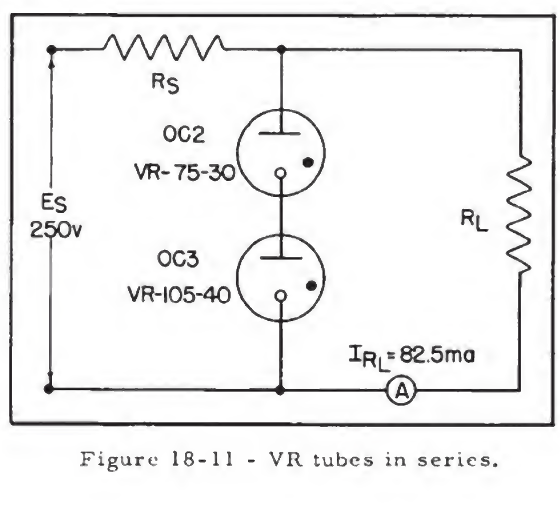

Figure 18-11 - VR tubes in series.

A9. The minimum current rating specifies the amount of current required to maintain ionization within the tube.

A10. Tube resistance increases.

A11. Tube ionization decreases.

In Figure 18-11 a VR75-30 and a VR105-40 are shown connected in series. The source voltage is 250V and 82.5 ma flows through the load resistance. Since current through the two VR tubes is common, the limits of regulation is determined by the tube having the smaller current limitations. (In this case, the VR75-30). In computing I_{mean} for this circuit, I_{max} and I_{mean} will be 30 ma and 5 ma respectively. Therefore, the mean current will be 17.5 ma.

The value of R_s in Figure 18-11 can be computed using the source voltage of 250V and the total current through R_s (load current + I_{mean}). Using these values, R_s = 700 ohms. It should be noted that the regulated voltage to the load is 180V. This provides a regulated voltage greater than would be possible using either VR tube by itself.

Another advantage of using VR tubes in series is illustrated in Figure 18-12. In this circuit, several values of regulated voltages are obtained from a single power supply.

The current flowing through V_2 in Figure 18-12 is a combination of the current through R_1 and the current through V_1. The current through V_3, on the other hand, is the sum of currents through V_2 and R_2. Since V_3 has more current flowing through it than any of the other VR tubes, it places a severe limit on the current's flowing in the VR tube circuits. Since the maximum rating of V_3 is 40 ma, the currents through R_1 and R_2 must be limited to only a few milliamperes or the rating of V_3 will be exceeded and regulation will cease.

The obvious advantage in using VR tubes in series is to provide several regulated voltages from a single power supply. The primary disadvantage is in the current limitations. Since it is impossible to have all VR tubes operating about their mean current values, this limits the ability of the circuit to regulate over wide ranges of variations in load resistance or source voltage.

Q12. What would be the value of R_s in Figure 18-11 if two VR90-40 tubes were used?

Q13. Would it be possible to obtain a regulated 270V using conventional VR tubes? If so, how?

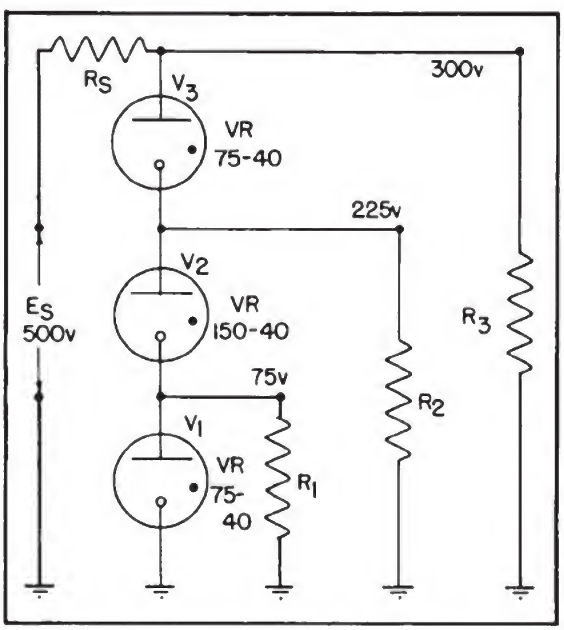

Figure 18-12 - VR tubes as voltage dividers.

18-8. VR Tubes Connected in Parallel

One might expect that connecting VR tubes in parallel (Figure 18-13) would increase the current handling capacity of the network. Although this statement is true in regards to the operation of some gas filled tubes, it is not true of VR tubes. To illustrate this fact, two VR tubes are connected in parallel across a load. Since no two VR tubes are constructed in exactly the same way, there will be a slight difference in their ionization potential. For the purpose of this discussion, VR tube VR_1 will have a lower ionization potential than VR_2. The potential that must be reached before a VR tube ionizes is considerably higher than its normal operating voltage.

When voltage is applied to the circuit of Figure 18-13 as soon as the correct potential is reached, VR_1 begins to conduct and the potential across it decreases to its operating voltage. The potential across VR_2 never

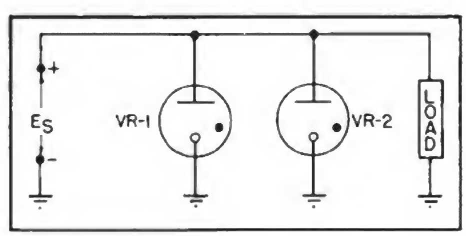

Figure 18-13 - VR tubes connected in parallel

becomes sufficiently high to cause it to ionize. Therefore, placing the VR tubes in parallel accomplishes no useful purpose. When greater current handling capacity and better regulation are desired, electronic (vacuum tube) regulator circuits are used.

18-9. Typical Voltage Regulated Power Supplies

Figure 18-14 shows a power supply having a regulated 150V and an unregulated 350V output. Note the jumper connection in the regulated 150V output. When V_2 is removed from the circuit, the jumper opens the 150V output. This safety feature protects the circuits connected to the 150V regulated output. Without the jumper, removal of the VR would cause current through R_2 to decrease. This would cause the 150V output to increase with possible adverse effects on the circuits connected to this power supply output.

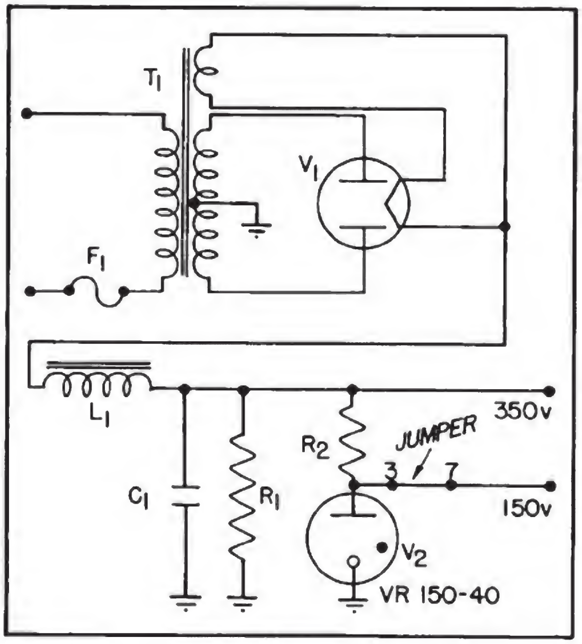

Figure 18-14 - Example of regulated/unregulated power supply.

Figure 18-15 shows a power supply using two VR tubes connected in such a fashion as to provide - 150V and +150V regulated outputs. By connecting ground between the two regulator tubes, the cathode of V_3 is made negative with respect to its anode while the anode of V_2 is positive with respect to its cathode. Series resistor R_2 is made variable to compensate for changes in internal resistance of the power supply.

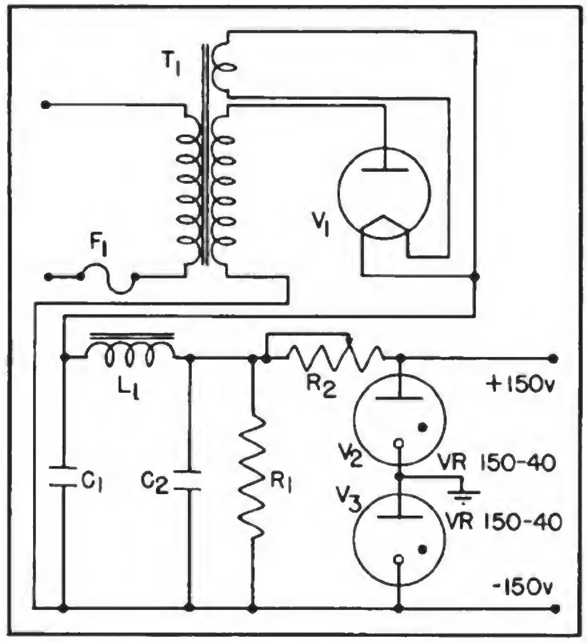

Figure 18-15 - Example of positive and negative regulated power supply.

Many other circuit configurations exist which use VR tubes. The particular use being determined by requirements to be achieved. In some cases, VR tubes are used to protect components from excessive current while other circuits make use of the VR tube's constant voltage as a reference.

Q14. Is it possible to have a regulated and an unregulated output from the same power supply?

A12. Since I_{mean} would now be 22.5 ma, total current would be 82.5 + 22.5 or 105 ma. To drop 70V at 105 ma, R_s would be approximately 667 ohms.

A13. One method would be to connect a VR75, a VR90 and a VR105 in series.

A14. Yes. Refer to Figure 18-14.

EXERCISE 18

1. Why is voltage regulation necessary?
2. Why is the voltage drop across a VR tube constant over its operating range?
3. Describe series regulation.
4. What is the disadvantage of using a variable resistor for voltage regulation?
5. What is meant by the term "ionizing potential"?
6. What determines the "ionizing potential" of a VR tube?
7. What purpose does the jumper serve?
8. What types of gases are used in VR tubes?
9. How are the free electrons obtained which form the plate current before ionization?
10. How are the plate current electrons obtained after ionization?
11. What is meant by the term "dark current"?
12. Would a VR150-40 ionize if 150V were placed across it?
13. Is there any voltage variation across a VR tube when operated in its normal range?
14. What are the possible disadvantages in using VR tubes for voltage regulators?
15. In Figure 18-10 if average load current were 150 ma, what would be the value of R_s?
16. What are the advantages and disadvantages of using series connected VR tubes as voltage dividers?

CHAPTER 19

TRIODE AMPLIFIERS

In 1907, Lee DeForest opened the door to what proved to be the birth of a new age in the history of man's technical advancement. By placing a small wire mesh or GRID into the diode, he discovered that electron flow from the cathode to the plate could be controlled by varying the grid potential. Since three active elements or electrodes were involved, the device was called a TRIODE.

The operation of the triode in controlling current flow was considered analogous to the action of a VALVE in controlling water flow. Due to this concept, the term valve was used originally in place of the present words VACUUM TUBE. Even today some countries, such as England, retain the word valve.

An interesting discovery associated with DeForest's triode vacuum tube is that a small grid potential can provide control over a much larger plate potential, by its ability to control current flow. This is to say that a small amount of power or energy can control a much larger amount of power or energy. This process is called AMPLIFICATION and is similar to the action of a throttle valve on a steam engine which controls a large amount of mechanical power or energy, though the power used in operating the valve is small.

Because of its ability to amplify, the triode made possible the initial advancements in the field of electronics. Few pieces of electronic equipment exist which do not contain amplifiers. In this chapter the use of triodes as AUDIO FREQUENCY AMPLIFIERS will be examined.

Transmitters and most other types of electronic equipment require more voltage, current, or power output than is available in the original input. To be useful, this input must be amplified. Since a transmitter modulator unit frequently uses triode amplifiers, a brief description of a modulator will be given to show an application of the triode amplifier.

MODULATORS

In most transmitters the power available from a microphone is far too small to directly modulate the RF carrier wave produced by the RF unit. This limitation can be overcome by amplifying the small microphone signal output before modulation occurs. The electrical location of a modulator is shown in Figure 19-1.

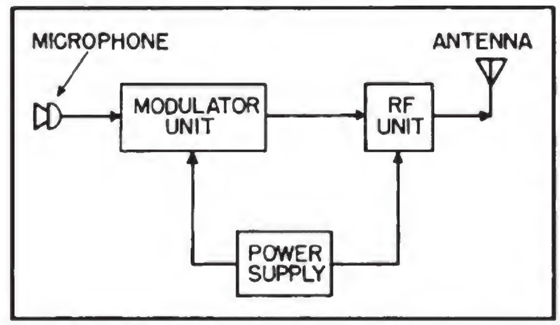

Figure 19-1 - Basic transmitter block diagram.

The modulator unit is frequently considered as the equipment from the microphone to the modulated stage in the RF unit. A block diagram of a typical modulator unit is shown in Figure 19-2.

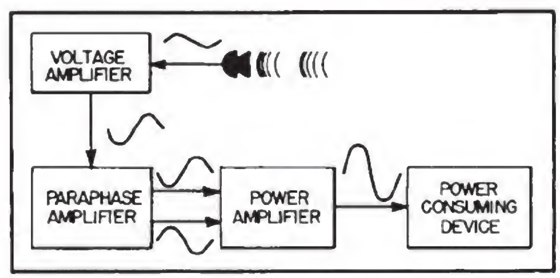

Figure 19-2 - Modulator block diagram.

The microphone converts sound energy into a small ac signal voltage which is applied to the voltage amplifier section of the modulator. The voltage amplifier greatly increases the signal voltage. From the voltage amplifier, the signal is applied to a paraphase amplifier (sometimes called a phase splitter) which provides two output voltages from the single input voltage. These two output signals are identical in appearance with the exception that one is inverted with respect to the other. Two signals are necessary because the type of power amplifier used contains two tubes and thus requires two input

signals. The power amplifier provides the necessary power for proper operation of the power consuming device. This device is normally the RF unit and possibly a loudspeaker used for monitoring purposes.

Q1. What would happen if the RF unit were directly modulated by the microphone?

PHYSICAL CHARACTERISTICS OF A TRIODE

19-1. Construction

The triode electron tube is similar in construction to the diode, the primary difference being the addition of a grid-like electrode placed in the area between cathode and plate. This electrode is called the CONTROL GRID and enables the tube to amplify by controlling the flow of plate current. The construction features of a typical triode are shown in Figure 19-3.

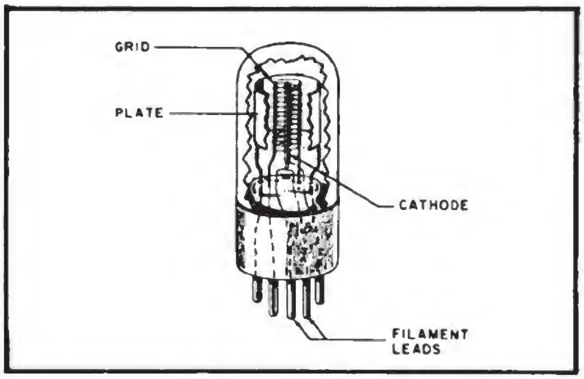

Figure 19-3 - Cut-away view of a triode.

Electrical connections to the cathode, grid, and plate are made through the base pins and support wires. The cathode sleeve is insulated from the heater and is connected, by means of a short lead, to one of the base pins. Note that the grid is located much closer to the cathode than to the plate.

Although in certain triodes gas is inserted in the tube, those which are used for voltage amplification are of the high vacuum type. In such tubes the air pressure within the glass or metal envelope is reduced to approximately one one-hundred millionth that of atmospheric pressure. Even with this high degree of evacuation, a large quantity of air molecules still remain, which could interfere with tube operation if means were not provided to eliminate them. As with the diode vacuum tubes studied previously, a getter is used to combine with the residual gas, or any gas which may be liberated from the heated elements after the tube is placed into operation.

The control grid of a triode is usually made of fine wire coiled into a helix and mounted on two supporting wires. Typical grid structures are shown in Figure 19-4.

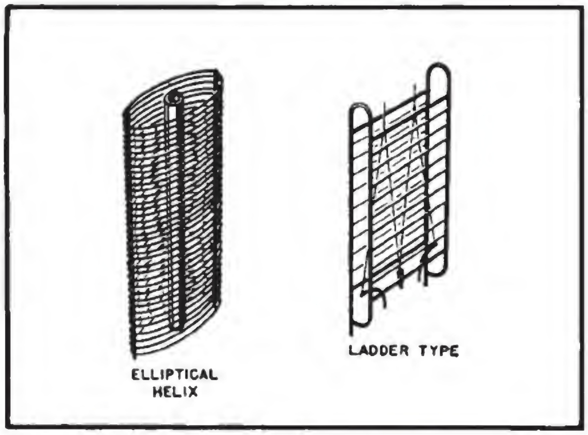

Figure 19-4 - Typical grid structures.

Low power triode grids are usually made of manganese nickel while high power triode grids are made of molybdenum compounds to reduce grid emission. Such emission is undesirable and can occur due to the influence of the intense electrostatic field between plate and grid when plate voltage is very high (as in high power tubes). The plate (anode) of triodes used for low power applications is made of nickel or iron. The plate is pressed out of sheet material in the form of a cylinder or other shape and completely surrounds the grid. For higher power uses the plate may be constructed of graphite or copper. In many cases the plate is provided with a rough surface, or is blackened to increase its ability to radiate heat caused by electron bombardment.

The physical structure and electrical symbol of an indirectly heated triode are shown in Figure 19-5. It can be seen that the oxide-coated cathode is located in the center of the tube structure. Surrounding the cathode is the helical shaped grid structure. The plate, in the form of a cylinder, completely encircles the grid. Regardless of the shape of the grid or plate, the grid must be placed so that the electrons emitted from the cathode will pass between the wires of the grid on their way to the plate. In the triode symbol the heater is shown beneath the cathode. It is common practice to omit the heater from this symbol to simplify schematic drawings. Where complete equipment schematics are encountered, the heaters of all the tubes will usually be shown near their source of power.

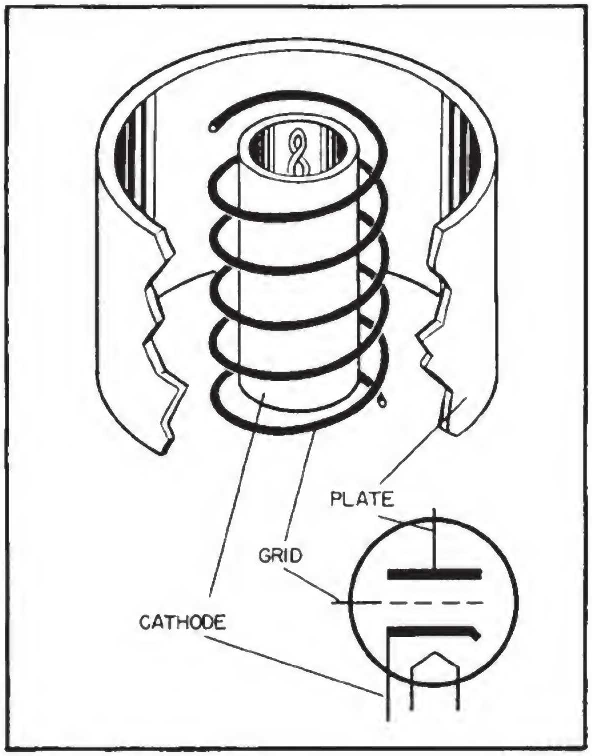

Figure 19-5 - Physical structure and schematic symbol of a triode vacuum tube.

Q2. Why is the control grid an open mesh rather than a continuous sheet of metal?

CONTROL OF PLATE CURRENT

During operation of a triode tube, various potentials are applied to the tube elements with respect to each other, and with respect to the equipment ground reference. The behavior of the electrons within the tube depends on the various electrostatic fields existing between the tube elements. The direction and intensity of these fields are governed entirely by THE DIFFERENCE OF POTENTIAL BETWEEN THE ELEMENTS of the tube, and NOT by the absolute potential of the element with respect to equipment ground. In this text, unless otherwise specified, ALL ELECTRODE POTENTIALS ARE MEASURED WITH RESPECT TO THE CATHODE. Thus, the statement "The plate voltage is 200 volts." is taken to mean "The plate-to-cathode voltage is 200 volts."

Since the electrons comprising the plate current of a triode must flow between the grid wires, the potentials of both the grid and plate are effective in controlling plate current. The grid, however, being closer to the cathode, has more control over plate current than does the plate. It is this feature which produces amplification in a triode vacuum tube.

To master the theory of the triode, it is necessary to learn how each of the physical and electrical factors of the tube and its associated circuitry affect the flow of plate current. Since for a given tube the physical factors (electrode spacing, pitch of grid wires, etc.) are fixed, the problem becomes one of voltage and current analysis.

In analyzing the operation of the triode vacuum tube, three independent variables and two dependent variables exist. The independent variables are cathode temperature, grid voltage, and plate voltage. The dependent variables are grid current and plate current. Normally cathode temperature is fixed and its effects are not encountered. To determine the effects of the two remaining independent variables, one is held constant while the other is varied.

Q3. How much plate voltage would there be on a tube if the plate-to-ground potential is 90 volts, and the cathode-to-ground potential is -40 volts?

19-2. Zero Grid Potential

Examination of triode operation will begin with a condition where grid potential is held at zero volts with respect to the cathode while plate voltage is varied. Consider the circuit of Figure 19-6 in which ammeters M_1, M_2, and M_3 are connected so that each meter is in series with a different element of the tube. M_2 and M_3 measure plate and cathode currents respectively, while M_1 measures any grid current which might flow. Plate voltage is supplied by a variable dc source E_{bb}, which can be adjusted to any desired value. Notice that the grid is connected to the cathode through meter M_1 thereby maintaining the grid at zero volts with respect to the cathode.

If E_{bb} is adjusted to zero volts, all tube elements are at the same potential and no electric fields of force exist between the tube elements. The electrons propelled outward from the heated cathode form a space charge in the

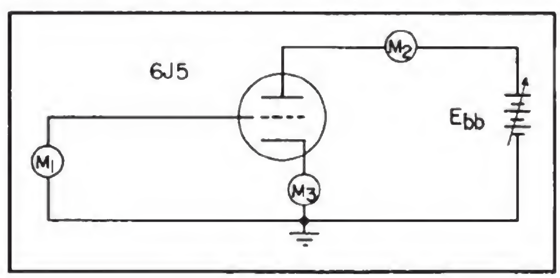

Figure 19-6 - Triode with zero volts grid potential.

A1. The transmitted signal would not be adequately modulated causing great difficulty in hearing the station in a receiver.

A2. An open mesh must be used so that the electrons to be controlled can pass through the grid on their way to the plate.

A3. Since plate voltage is measured between plate and cathode the plate voltage would be +130 volts.

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immediate vicinity of the cathode surface. Since the emission velocities of the electrons are small, few electrons have sufficient energy to travel as far as the grid or plate. For all practical purposes, no grid or plate current flows when the potentials applied to these two elements are zero.

If the control grid is maintained at zero volts and the plate supply E_{bb} is adjusted to 25 volts, an electrostatic field will be established within the tube. The lines of force representing this field are illustrated in Figure 19-7. Notice that each line of force originates on a positive charge contained by the plate, and terminates on the control grid, space charge, or cathode. When the grid is at zero potential, the majority of the lines of force will terminate on the outer electrons in the space charge rather than on the control grid or cathode. Since the space charge electrons have great mobility, they will be attracted to the plate along one of the lines of force illustrated. As the electrons travel from the space charge to the plate, they absorb energy from the electric field established by the plate voltage, and their velocity increases. Upon striking the plate, the electrons surrender this kinetic energy to the plate in the form of heat. If the plate is not to be damaged, it must be capable of radiating the excess heat. Each tube has a MAXIMUM PLATE DISSIPATION RATING, specified by the manufacturer, which ultimately places a limit on the maximum values of current and voltage that can be used.

For each electron removed from the space charge by the positive plate, an additional electron is supplied to the space charge by the cathode. Due to this action, a continuous current flows from cathode to plate within the tube, and from the plate through the dc source to the cathode in the external circuit. This path comprises a simple series circuit and the plate and cathode meters would indicate equal currents.

As the positive plate attracts electrons from the space charge, it is unavoidable that a few of these electrons collide with the wires of the control grid. When an external dc connection

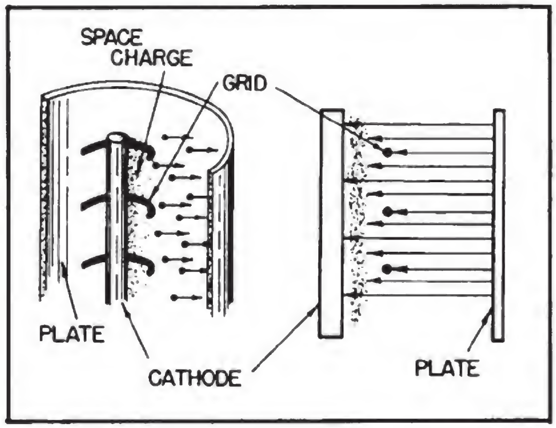

Figure 19-7 - Electrostatic field with zero grid potential.

is provided between grid and cathode, these electrons trickle from the grid and return to the cathode. This flow of electrons is very minute and is not normally regarded as true grid current. Thus, a milliammeter connected into the grid circuit would not indicate a flow of current.

If the grid of a triode vacuum tube should become open, the electrons which accidently strike the grid are trapped and cannot return to the cathode. As electrons accumulate on the grid wires, the grid develops a negative charge which repels the electrons leaving the space charge. This negative charge will reduce the plate current, or in severe cases may stop it entirely. The tube is then said to have a BLOCKED GRID or FLOATING GRID.

To prevent the accumulation of a negative charge on the grid, a dc path must always be provided between grid and cathode, In most amplifier circuits, this path is provided by a resistor connected in the external grid-to-cathode circuit. Since this resistor allows the electrons to "leak" from the grid to the cathode, it is called a GRID LEAK RESISTOR.

With zero grid potential and a plate potential of 25 volts, the 6J5 triode conducts a plate current of 1.8 ma. If the plate voltage is increased to 50 volts, the intensity of the electrostatic field between plate and cathode is increased and more electrons are attracted to the plate. With 50 volts on the plate, plate current is 4.2 ma, an increase of 2.4 ma over the value obtained for a plate voltage of 25 volts. If plate voltage is increased an additional 25 volts, plate current will increase to 7.2 ma. Thus, the relationship between plate voltage and plate current in a triode is similar to that observed in the diode.

Q4. What is the maximum plate current that can be safely passed through a triode tube, at a plate voltage of 300 volts, if the maximum plate dissipation rating of the tube is 9 watts?

19-3. Positive Grid Potential

If positive potentials are applied to both the plate and control grid of a triode, each of these electrodes will draw current. The positive grid will attract electrons and cause them to be accelerated toward the grid. Some electrons are attracted to the grid, resulting in GRID CURRENT. The remainder of the electrons pass between the grid wires and continue to the plate. The more positive the grid potential, the greater the grid and plate currents. For example, with the 6J5 triode, if the grid potential is +4 volts and the plate potential is 75 volts, the grid will draw 3 ma and the plate 17.5 ma of current. If the plate potential is maintained at 75 volts but grid potential is increased to +8 volts, the grid and plate currents will be 7.0 ma and 31.2 ma, respectively.

It should be noted that with a constant plate potential of 75 volts, a large change in plate current occurs as the grid potential is varied from +4 to +8 volts. This indicates that the grid has a very substantial amount of control over plate current. In fact, due to the closeness of the grid to the cathode, the grid voltage has a much greater effect on plate current than does plate voltage.

Q5. If the grid and plate potentials are +2 and +80 volts respectively, what change if any should occur in plate current if plate voltage is increased 20 volts?

19-4. Negative Grid Potential

In most audio amplifiers, operation of the tube with a positive grid is undesirable. The grid current which results from this type of operation causes a power loss in the grid circuit and in many cases will also cause distortion of the signal. Because of this fact, the control grid of an audio amplifier is normally maintained negative at all times.

If the grid is made somewhat negative with respect to the cathode, the electric field within the tube will have the same general appearance as when the grid was at zero potential (see Figure 19-8). However, in the case of a negative grid, a greater percentage of the lines of force generated by the plate will terminate on the control grid and less lines of force will terminate on the space charge electrons. Since less lines of force reach the space charge, the plate is not able to attract as many electrons as when the grid was at zero potential. Applying a negative potential to the grid thus reduces plate current.

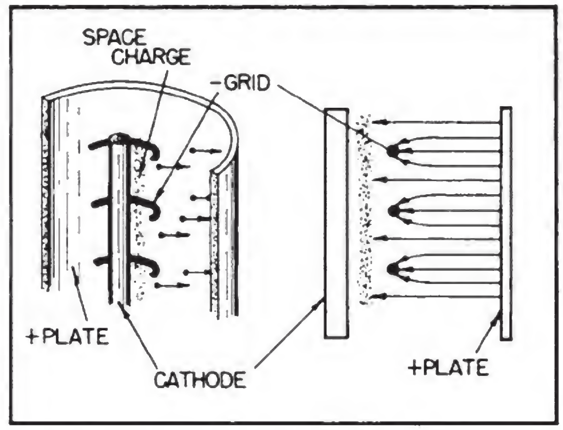

Figure 19-8 - Electrostatic field for a triode with a negative grid.

As the grid potential is made increasingly negative, more and more lines of force from the plate terminate on the grid and fewer terminate on the space charge. As a result, plate current becomes smaller. Eventually a point is reached where the grid is sufficiently negative to prevent all of the lines of force from reaching the space charge. All of the lines of force terminate on the control grid. When this happens, plate current cannot flow and the tube is said to be CUT OFF. The negative potential required to achieve this condition is called the CUT-OFF VOLTAGE (E_{co}). Figure 19-9 shows the shape of the electrostatic field for a grid voltage equal to, or greater than the cut-off value.

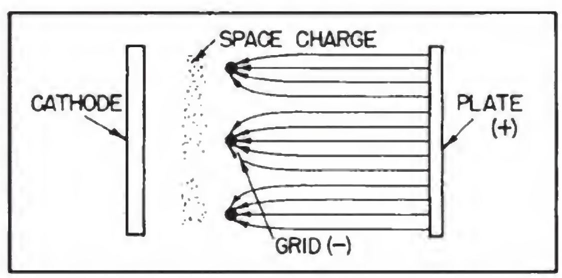

Figure 19-9 - Electrostatic field at or beyond cut-off.

Q6. Assuming the grid voltage of a certain triode is just sufficient to place the tube into cut-off, what would be the effect of a substantial increase in plate voltage?

TRIODE CHARACTERISTIC CURVES

One of the most convenient methods of presenting information on a specific vacuum tube is by means of characteristic curves. In this

A4. 30 milliamperes. The plate dissipation in watts is equal to $E_b \times I_b$.

A5. Plate current should increase.

A6. The tube would begin conducting, as it would now require a larger negative potential on the grid to hold the tube in cut-off at the higher plate voltage.

way, the otherwise complex relationships between grid voltage, plate current, and plate voltage can be shown simply and directly. Neglecting grid current and variations in cathode temperature, there are three possible graphs that can be constructed for the triode vacuum tube. In plotting each of these three graphs, one of the tube variables (E_c, I_b, or E_b) is held constant, the second quantity is varied, and the effects on the third quantity are measured. Curves that are obtained without using a load resistor and which represent the characteristics of the tube itself are called STATIC CURVES. Curves which include the effects of the load are called DYNAMIC CURVES.

19-5. Grid Family of Curves

If plate voltage (E_b) is held constant, the relationship between grid voltage (E_c) and plate current (I_b) can be observed. To illustrate this, assume that a constant 100 volts is applied to the plate of a 6J5 triode. If the grid voltage is

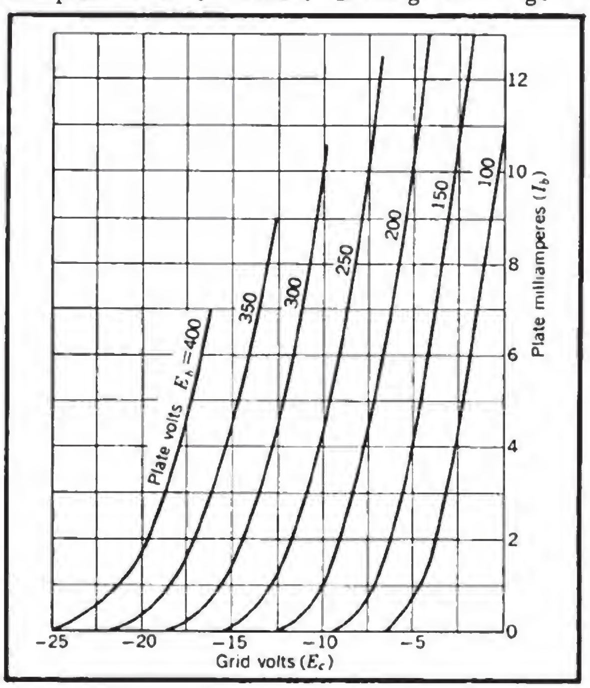

Figure 19-10 - Grid characteristic curves.

adjusted to a number of different values in succession, and the plate current is measured for each of these grid potentials, a curve like the one labeled "100" in Figure 19-10 can be constructed. This curve is called an "E_c-I_b" curve and is useful because it shows the value of plate current that is obtained for any value of grid voltage between zero and the cut-off grid voltage of -6.5 volts.

A single E_c-I_b curve is of very limited value since it is only valid for one value of plate voltage. Generally, a number of such curves are plotted on the same graph, each curve representing a different plate voltage. The resulting group of curves is called a "family" of curves. Since the independent variable used in plotting the curves is grid voltage (E_c), the graph is called the GRID FAMILY OF CHARACTERISTIC CURVES or simply GRID CHARACTERISTICS.

To see how these curves can be used, assume it is necessary to find the grid voltage required to produce a plate current of 4 ma at a plate voltage of 150 volts. First, move up the I_b axis until the horizontal line representing 4 ma is located. Next, find the point where this line intersects the 150 volt plate voltage curve. Finally, from the point of intersection drop a line perpendicular to the E_c axis. This line cuts the E_c axis at -5 volts, showing that -5 volts grid voltage is required to cause 4 ma of plate current at 150 volts plate voltage.

Q7. How much negative grid voltage is required to prevent conduction of the tube at a plate voltage of 200 volts?

19-6. Plate Family of Curves

Another set of static characteristic curves is obtained by holding grid voltage constant and measuring the effect of plate voltage on plate current. Since plate voltage is the independent variable, this family of curves is called the PLATE CHARACTERISTICS, or E_b-I_b curves.

The plate family of curves is developed by a method very similar to the one used to produce the grid family. To obtain the first curve ($E_c = 0$) shown in Figure 19-11, the grid potential is adjusted to zero volts. Then starting at zero, the plate voltage is increased in steps, and the plate current for each of these plate voltages is recorded. From the recorded values a curve is plotted and marked $E_c = 0$.

The second, third, etc. curves are obtained by repeating the above procedure with grid potentials of -2 volts, -4 volts, etc. Notice, that all of the curves have the same general shape. They differ mainly in position, the curves representing the higher grid voltages being displaced farther to the right along the plate voltage axis.

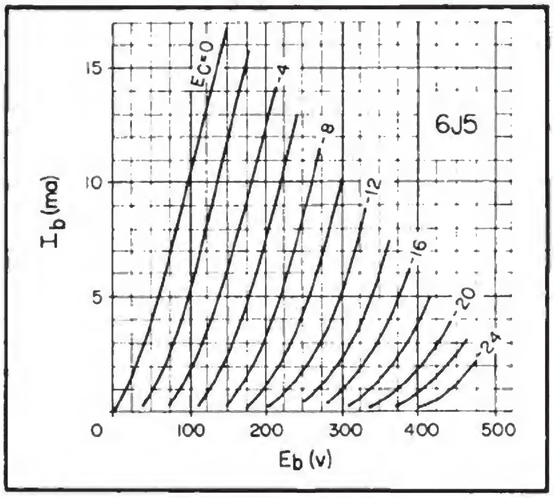

Figure 19-11 - Plate characteristic curves.

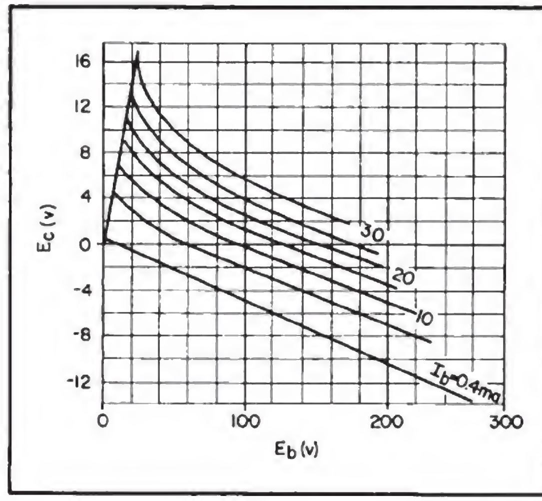

Figure 19-12 - Constant current curves.

Because they are convenient to use, the plate characteristic curves are the ones most often published in tube manuals. Since essentially the same information is contained in all three families of curves, it is possible to derive the other two families from the plate family should their use be required.

To demonstrate one use for the plate family of curves, assume it is necessary to determine the amount of plate current that would be obtained at a plate voltage of 275 volts and a grid voltage of -10 volts. First, locate the vertical line in Figure 19-11 that represents 275 volts plate voltage. Find the point where this vertical line intersects the -10 volt curve. As read from the plate current axis, this intersection represents a plate current of 7 ma.

Q8. If grid voltage is maintained at a constant -10 volts, how much will plate current change if plate voltage is changed from 200 volts to 275 volts?

19-7. Constant Current Family of Curves

The third family of characteristic curves is called the CONSTANT CURRENT or E_c-E_b characteristic curves. To construct the constant current curves plate voltage is used as the independent variable and is plotted horizontally along the X-axis.

To obtain the points for the curve, the grid voltage required to produce the desired current is determined for a number of different plate voltages. The various combinations of plate voltage and grid voltage which produce the same value of current are then plotted to obtain the constant currrent curve.

A constant current family of curves is shown in Figure 19-12. Notice, that each curve represents a different value of current, rather than voltage values as in the two previous families of curves. Although the constant current curves are not quite so common as the plate family they are used extensively in the study of radio frequency amplifiers.

TRIODE AMPLIFYING ACTION

19-8. The Basic Voltage Amplifier

Triode vacuum tubes are used extensively as voltage amplifiers. As was explained in the previous topic, variations in grid voltage cause variations in plate current. These variations in plate current must be converted to voltage variations if the circuit is to provide voltage amplification.

Figure 19-13 shows a triode with its control grid connected to a sinusoidal voltage source e_i, while the plate is connected to a constant voltage source E_{bb}. A "constant voltage source" is one having perfect regulation. That is, any amount of current can be drawn from the source

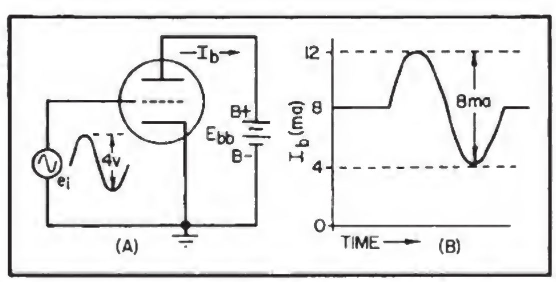

Figure 19-13 - Effects on I_b with sinusoidal grid voltage.

A7. Approximately -12.5 volts.

A8. Plate current will change 6 ma, since at 200 volts it is 1 ma and at 275 volts it is 7 ma.

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without causing a change in source voltage.

The sine wave of voltage applied between grid and cathode of the tube causes plate current to vary in a sinusoidal fashion as shown in part B of Figure 19-13. Since the input signal has a peak-to-peak amplitude of 4 volts, the grid will reach a potential of plus 2 volts at the peak of the positive alternation, and a minus 2 volts at the peak of the negative alternation.

During the positive excursion of the input signal the plate current will rise from its no signal value of 8 ma, to its peak positive value of 12 ma. Upon completion of the positive alternation the grid becomes negative, causing plate current to decrease. At the peak of the negative alternation the plate current decreases to its minimum value of 4 ma. Thus, as the grid completes one cycle of voltage, a similar sinusoidal variation occurs in plate current.

Notice that, although a peak-to-peak plate current variation of 8 ma occurs, there is no variation in plate voltage. The plate voltage remains at the constant value of E_{bb}. In order to convert the changes in plate current into changes in plate voltage a resistor (or other impedance) must be inserted between the plate of the tube and the positive terminal of E_{bb}, as shown in Figure 19-14. This resistor is called a PLATE LOAD RESISTOR (R_L). From a dc standpoint R_L is in series with the plate of the tube and, therefore, carries the total dc plate current.

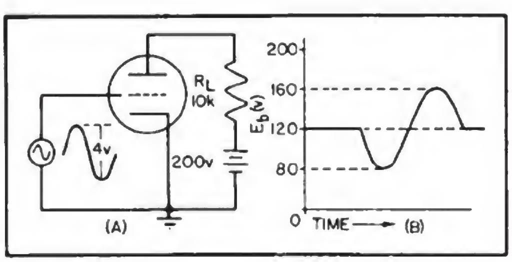


Figure 19-14 - Vacuum tube amplifier circuit showing load resistance.

To explain the operation of the circuit, the 4 volt peak-to-peak input signal will again be assumed to produce an 8 ma peak-to-peak change in plate current. Referring to Figure 19-14, when the grid signal is at zero the plate current is 8 ma. With 8 ma of current through the 10,000 ohm plate load resistor, the resistor will drop 80 volts. Since E_{bb} is 200 volts, the plate voltage (E_b) will be equal to the supply voltage minus the drop across the plate load resistor or:

$$E_b = E_{bb} - E_{RL}$$
$$E_b = 200 - 80$$
$$E_b = 120 \text{ volts}$$

As the grid signal reaches its positive peak the plate current will rise to 12 ma. At the positive peak of the grid signal the plate voltage will be:

$$E_b = 200 - 120$$
$$E_b = 80 \text{ volts}$$

Notice that, as the grid signal changes from zero to +2 volts in the positive direction, the plate voltage falls from 120 to 80 volts. As the grid signal returns to zero, completing the positive alternation, the plate current and plate voltage return to their original values of 8 ma and 120 volts respectively.

Comparing the grid and plate voltage variations shows that, as the grid signal progresses through a positive alternation having a peak amplitude of 2 volts, the plate voltage completes a negative-going alternation of 40 volts. Close attention should be given to the fact that, in addition to being amplified by a factor of 20, THE OUTPUT SIGNAL IS INVERTED with respect to the input signal.

During the onset of the negative alternation of the input signal, plate current will decrease and plate voltage will rise. When the grid reaches its peak negative value of -2 volts the plate current will be 4 ma and the plate voltage will be 160 volts. Consequently, a negative-going grid signal will produce a positive-going plate signal, and as before the output is inverted with respect to the input.

Although the signal applied to the grid is a true alternating voltage, the signal developed at the plate of the tube is a direct voltage which varies in amplitude in accordance with the grid signal.

Q9. What would the plate voltage be in the circuit shown in Figure 19-14 for a plate current of 2 milliamperes?

Q10. What would the plate voltage be if the grid was made negative enough to cut off plate current?

THE DC LOAD LINE

It is often necessary to be able to compute the voltage gain, signal amplitude, or output power of an amplifier circuit. The analysis of a triode amplifier can be obtained mathematically

through equations written for the circuit, or by graphical means using one of the families of curves developed previously. Because of its simplicity, the graphical method of analysis will be presented first.

When the three families of triode curves were introduced, it was pointed out that the curves describe the operation of the tube alone, and do not show the effects of the plate load resistor. In order to make the curves useful for the analysis of an amplifier circuit, the graph must be modified to take the effects of the load resistor into consideration. This is done by plotting an additional line on the family of curves. Since this line represents the effects of the load it is called a LOAD LINE.

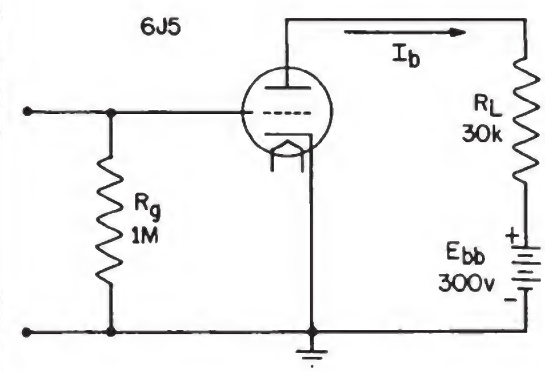
19-9. Constructing the DC Load Line

In most cases the analysis of an audio amplifier circuit is carried out using the plate family of curves. This procedure will be illustrated using the circuit in Figure 19-15, and the plate family of curves in Figure 19-16.

If the amount of plate current in Figure 19-15 is known, the voltage across the load resistor and across the tube can be computed. For example, assume the dc plate current (I_b) is 1 ma. Since the plate current (I_b) flows through R_L, the drop across R_L is equal to I_b times R_L, or 30 volts. The 30 volts dropped across R_L subtracts from the 300 volts supplied by E_{bb}, leaving 270 volts across the tube. This 270 volts is the plate voltage (E_b). Thus, IF the plate current was 1 ma the plate voltage would be 270 volts, as shown in Chart 1.

Had the value of assumed plate current been 3 ma, 90 volts would be dropped across the load resistor and 210 volts would drop across the tube. For a current of 5 ma the plate voltage is 150 volts. Notice, that as the tube conducts more heavily the voltage across it becomes lower. If the tube could be made to conduct a current of 10 ma the entire 300 volts of E_{bb} would be dropped across the load resistor and the plate voltage would be zero. At the other extreme, if the tube was driven into cut-off, plate current would be zero, no drop would occur across the plate load resistor and the plate potential would be equal to the supply potential of 300 volts.

All of the values of plate current and plate voltage in the preceding paragraph are tabulated in CHART 1 of Figure 19-15. Note the result when each set of values from CHART 1 is transferred to the plate family of curves in Figure 19-16. For example, the point representing 1 ma of plate current and 270 volts of plate voltage is marked point A in Figure 19-16. By plotting the plate for I_b = 3 ma, point B is obtained.



	I_b	E_L	E_b
A	1 ma	30 V	270 V
B	3 ma	90 V	210 V
C	5 ma	150 V	150 V
Y	10 ma	300 V	0 V
X	0 ma	0 V	300 V

CHART 1

Figure 19-15 - Example circuit.

The two extreme values of plate current produce point X (0 ma, 300V) and point Y (10 ma, 0V).

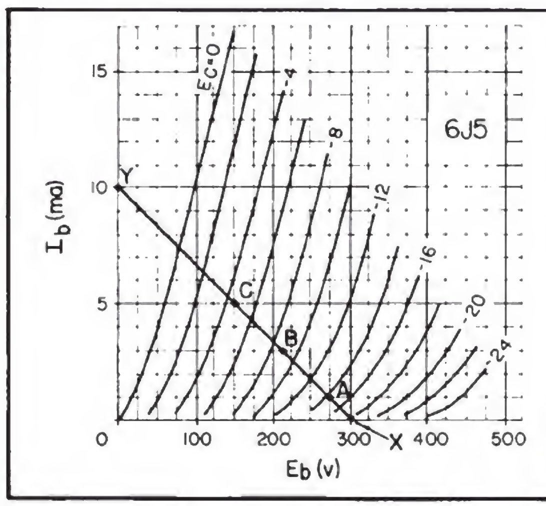


Figure 19-16 - Plate family of curves for 6J5.

Of great significance is the fact that ALL OF THE ABOVE MENTIONED POINTS LIE ON A SINGLE STRAIGHT LINE. This line, shown

A9. 180 volts. Since 20 volts would be dropped across R_L, the remaining 180 volts would appear across the tube.

A10. 200 volts. In the absence of plate current no drop would occur across R_L and both ends of R_L would be at the same potential of 200 volts.

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as X-Y in Figure 19-16, is called the DC LOAD LINE. Further examination of the circuit shows that ALL possible combinations of plate current and plate voltage for the circuit of Figure 19-15 must lie on this line.

Since the dc load line is drawn for a fixed resistance, and is therefore a straight line, only two plot points are required to establish its location. Although any two values of assumed current could be used to locate these two points, the extreme values of current are the most convenient. By using the maximum and minimum values of current, the points where the load line intercepts the plate voltage (X) axis and plate current (Y) axis are obtained.

To locate the X-axis intercept, the tube is assumed to be in cut-off. This sets values of zero ma and 300 volts for plate current and plate voltage, and establishes the point where the load line meets the plate voltage axis.

To locate the point where the load line intercepts the plate current or Y-axis, the tube is assumed to be conducting so heavily as to appear as a short circuit. The maximum plate current is therefore determined by the value of the supply voltage and the ohmic value of the plate load resistor. Numerically, this current is equal to E_{bb} divided by R_L. The two intercept points are located as follows:

The X-axis intercept occurs at the point where:

$$I_b = 0$$
$$E_b = E_{bb}$$

and the Y-axis intercept occurs at:

$$I_b = \frac{E_{bb}}{R_L}$$

$$E_b = 0$$

After these two points are established, a straight line is drawn between them and the construction of the load line is completed.

It should be noted that the location of the load line depends on the values of E_{bb} and R_L used in the circuit. The plate voltage intercept (X-axis intercept) depends only on the value of E_{bb}; whereas, the plate current intercept (Y-axis intercepts) depends on the values of both E_{bb} and R_L.

Once the dc load line is established for a particular amplifier circuit, only one of the three variables (E_b, I_b, E_c) need be known in order to determine the other two. This is true since all possible combinations of E_b, I_b, and E_c must lie somewhere along the load line. For example, to find the values of plate current and plate voltage that would exist in the circuit of Figure 19-15 at a grid potential of -12 volts, find the point where the -12 volt curve and the load line intersect. If two lines are passed through the point of intersection, perpendicular to the current and voltage axes, values can be obtained for E_b and I_b. For -12 volts grid potential the plate voltage is 250 volts and the plate current is 1.7 ma. Similarly, if the plate voltage were given, the corresponding values of plate current and grid voltage could be found.

LOAD LINE ANALYSIS

A complete triode amplifier circuit is shown in Figure 19-17. The signal to be amplified is a sine wave (e_i) having a peak amplitude of 4 volts. This signal is applied to the input terminals of the amplifier and appears across grid leak resistor R_g. As explained earlier, a positive potential applied to the control grid of a triode will cause grid current and an undesirable loss of power in the grid circuit. To prevent the input signal from driving the grid of the tube positive, a battery (E_{cc}) is connected into the grid-to-cathode circuit. The voltage supplied by this battery is called the BIAS voltage, and is an important factor in determining the characteristics of the amplifier. The purpose of bias, and the various methods used to obtain bias will be the subject of a subsequent topic.

The amplified and inverted output signal (e_o) appears between the plate of the tube and ground. Notice, that the plate circuit of the amplifier can be considered as EITHER a series circuit or a parallel circuit depending on the frame of reference used. If the plate circuit is considered from the standpoint of dc plate current (I_b), the tube, load resistor, and power supply (E_{bb}) comprise a series loop. From the standpoint of signal voltage (e_o), the plate circuit of the amplifier is a two branch parallel circuit in which the cathode-to-plate section of the tube forms one branch, and the load resistor and power supply form the second branch. The output signal appears across the two parallel branches. This concept can be compared to an LC tank circuit in which the coil and capacitor are in series as far as the circulating current

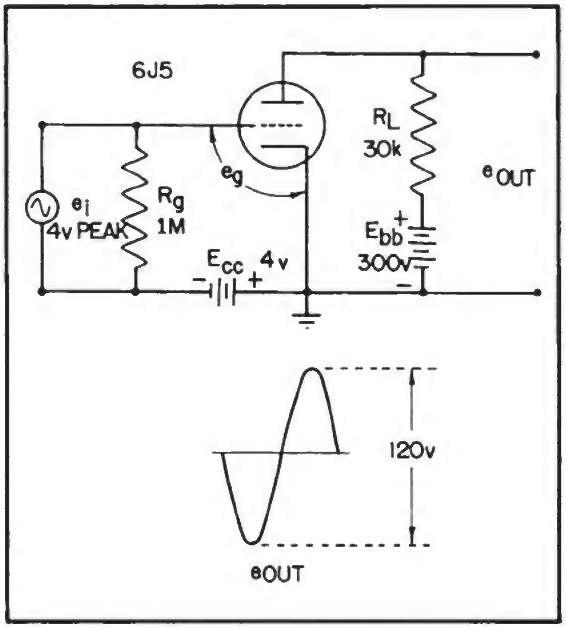

Figure 19-17 - Complete triode amplifier circuit.

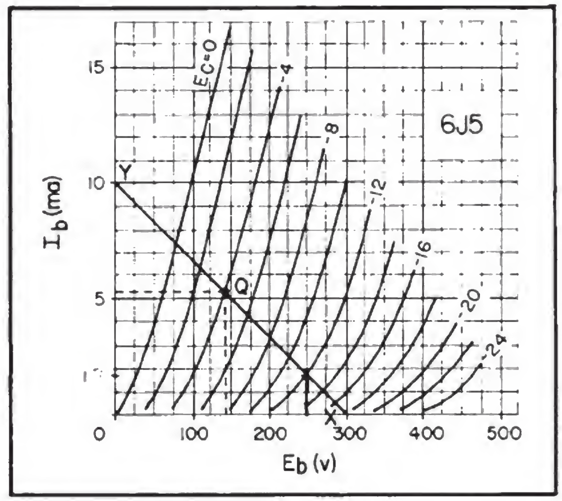

Figure 19-18 - Amplifier dc load line.

is concerned, but are in parallel when considering the sine wave of voltage across the tank. The circuit in Figure 19-17 is referred to as a single STAGE of amplification, and will now be analyzed by means of a load line.

19-10. Quiescent Operation

The first step in the analysis of the amplifier circuit in Figure 19-17 is to determine the magnitude of the dc currents and voltages that exist in the circuit. These currents and voltages are most readily examined when no signal is applied to the amplifier. When the amplifier is operating without a signal it is said to be in a QUIESCENT STATE, the word quiescent being derived from the word quiet. The currents and voltages which exist throughout the amplifier when no signal is applied are called the quiescent currents and voltages.

The quiescent values of current and voltage in the amplifier circuit of Figure 19-17 can be determined by constructing a load line on the plate family of curves shown in Figure 19-18. To determine the X-axis intercept for the load line, the tube is assumed to be in cut-off. This sets the values of plate current and plate voltage at 0 ma and 300 volts, establishing point X in Figure 19-18 as one end of the load line.

The Y-axis intercept is determined by assuming the tube to be conducting so heavily as to appear as a short circuit. This sets values of 10 ma and 0 volts for plate current and plate voltage, establishing point Y as a second point on the load line. The load line is completed by drawing a straight line between points X and Y.

To determine the quiescent plate voltage and plate current, the OPERATING POINT (Q) must be located on the load line. To locate the operating point, one of the three variables E_c, E_b, or I_b must be known. In the circuit of Figure 19-17, E_c is the known variable. With no input signal applied, the dc grid voltage (E_c) is equal to the grid supply voltage (E_{cc}). Thus, the operating point is located at the intersection of the -4 volt curve and the load line. This point is marked Q in Figure 19-18. The values of plate current and plate voltage for this operating point are shown by the dotted lines in Figure 19-18 and are 5.4 ma and 140 volts respectively. Since 140 volts are dropped across the tube, the difference between 140 volts and 300 volts, or 160 volts will appear across the load resistor.

Q11. What would be the plate current in the circuit shown in Figure 19-17 if the plate voltage was 100 volts?

19-11. Operation with an Input Signal

When an input signal is applied to the amplifier, the voltage between grid and cathode at any instant of time is equal to the sum of the signal voltage and the dc bias voltage. During the positive alternation of the applied signal, the signal voltage opposes the negative bias voltage causing the grid to become less negative. If the peak value of the signal is larger than the bias the grid will be driven positive for a portion of the alternation causing a flow of grid current, a normally undesirable condition in an audio amplifier. Thus, to avoid grid current and the

A11. The 100 volt line intersects the load line at a plate current of 6. 6 ma.

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distortion it usually produces, the peak signal voltage should never exceed the bias voltage.

For the duration of the negative alternation the signal voltage and the negative bias voltage have the same polarity and are, therefore, series-aiding. During this period of time the grid will be more negative than the bias voltage,

In the amplifier being analyzed the peak amplitude of the signal is equal to the 4 volt negative bias. Therefore, starting with the positive alternation, one cycle of input signal would cause the grid voltage to vary from -4 volts to 0 volts, to -4 volts, to -8 volts, and back to -4 volts. Hence the instantaneous grid voltage varies between the extreme values of 0 volts and -8 volts.

Since the changes in grid voltage are known, the changes in plate voltage and current can be determined by superimposing the input signal on the load line shown in Figure 19-19.

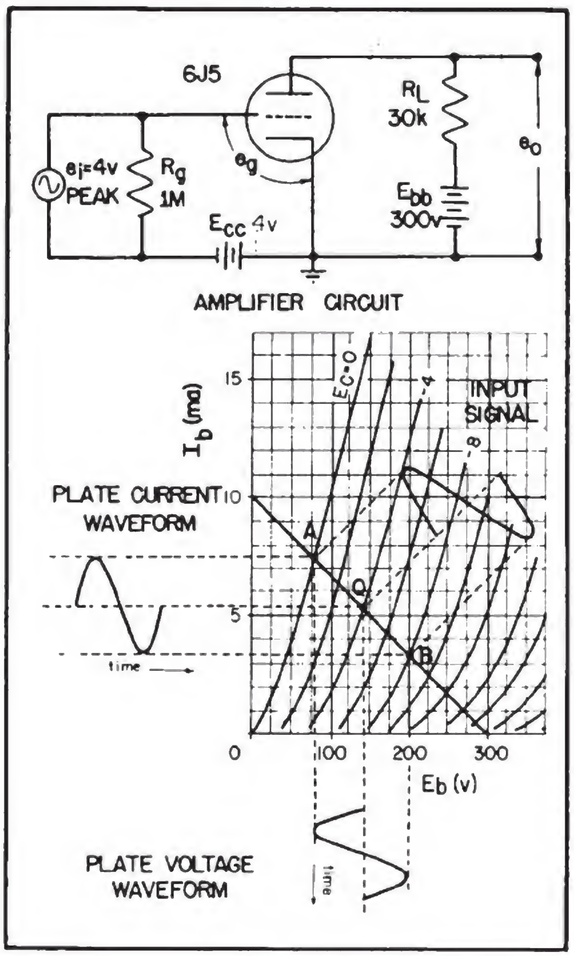

Figure 19-19 - Load line with signal applied.

At zero degrees on the input signal the grid voltage is -4 volts and the operating point is the same as the quiescent operating point. As the signal progresses through the first 90°, the positive-going signal voltage opposes the bias causing the grid to become less negative. As the grid becomes less negative, the instantaneous operating point moves up the load line from point Q towards point A. At 90° the signal attains its peak positive value of 4 volts and completely cancels the negative bias. At this instant the operating point has shifted up the load line to point A. Thus, at the positive peak of the input signal the plate current will increase from its quiescent value of 5. 4 ma to its maximum value of 7. 4 ma, and plate voltage will drop from its quiescent value of 140 volts to approximately 80 volts. During the second 90° of the positive alternation plate current decreases, plate voltage increases, and the instantaneous operating point moves back down the load line, reaching point Q at 180°.

As the input sine wave begins its negative alternation, the signal voltage aids the bias in making the grid negative. As the grid becomes increasingly negative, the instantaneous operating point moves down the load line from point Q to point B. At the negative peak of the signal, the plate current is approximately 3. 4 ma and plate voltage is 200 volts. During the remaining 90° of the cycle (270° - 360°) the current and voltage return to their quiescent values.

From the load line it can be seen that one complete cycle of input voltage causes a peak-to-peak variation in plate current of 4 ma, and a peak-to-peak variation in plate voltage of 120 volts. The relationship between E_c, E_b, and I_b is shown in Figure 19-20. Note in particular that the grid voltage and plate current variations are in phase with the input signal, while the plate voltage waveform is inverted with respect to the input signal.

Inasmuch as the voltage sine wave in the plate circuit is larger than the voltage sine wave in the grid circuit, amplification of the signal has occured. The number of times the signal has been amplified is called the GAIN (A) of the amplifier. Amplifier voltage gain (Av) is found by dividing the output signal voltage by the input signal voltage. The voltage gain of the amplifier in Figure 19-19 can be computed using the following equation:

$$A_v = \frac{E_o}{E_i} \qquad (19\text{-}1)$$

where: A_v = voltage gain
E_o = output signal voltage (peak, RMS, etc.)
E_i = input signal voltage in the same units as E_o

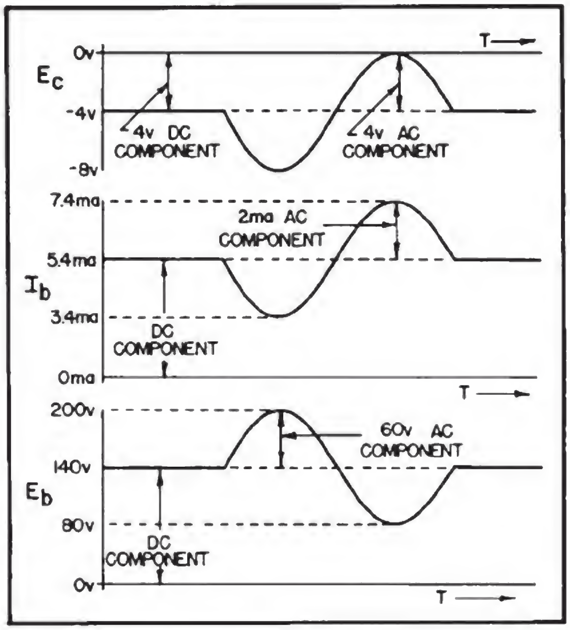

Figure 19-20 - Amplifier waveforms.

Since the peak-to-peak input signal to the amplifier is 8 volts and the peak-to-peak output signal is 120 volts the gain is:

$$A_v = \frac{E_o}{E_i} \qquad (19\text{-}1)$$

$$A_v = \frac{120}{8}$$

$$A_v = 15$$

Q12. What would the gain be for an input signal of 4 volts peak-to-peak?

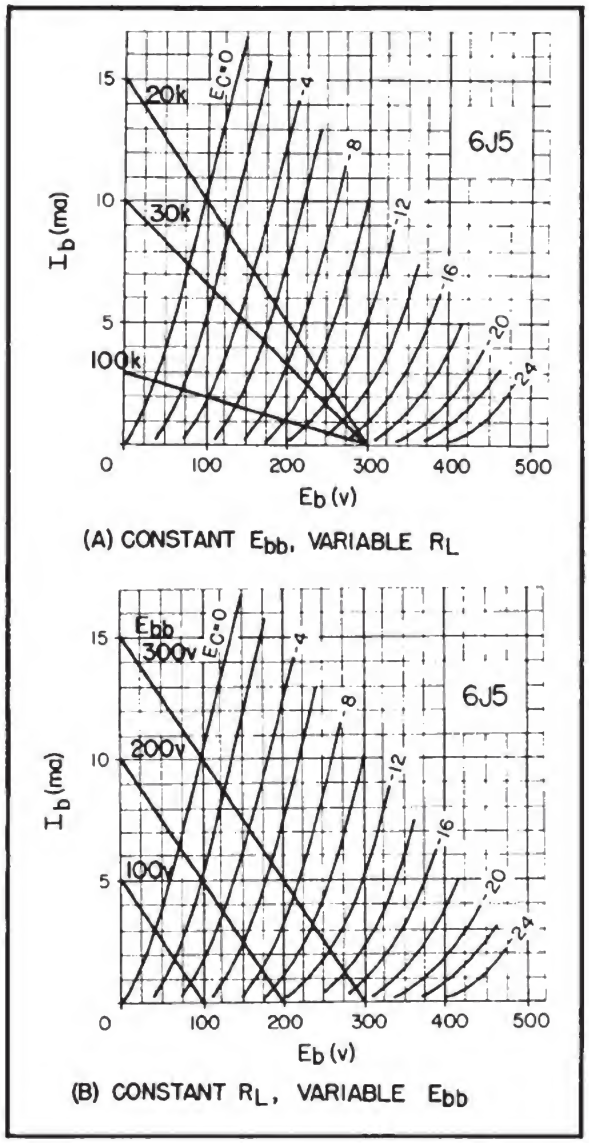

Figure 19-21 - Effects of load resistance and supply voltage on the dc load line.

19-12. Factors Affecting the Load Line

The slope and position of the load line are mainly dependent on the magnitude of the load resistance and the amount of supply voltage. Part (A) of Figure 19-21 shows a comparison of load lines representing load resistors of 20,000 ohms, 30,000 ohms, and 100,000 ohms, for a fixed supply voltage of 300 volts. As the load resistance is changed, the slope of the load line and the Y-axis intercept change, while the X-axis intercept remains fixed at 300 volts. Numerically, the slope of the dc load line is equal to $-1/R_L$.

As the ohmic value of the load resistor is increased, the Y-axis intercept occurs at a lower value of current, and the load line approaches a horizontal position. A close examination of Figure 19-21A shows that, for a given change in grid voltage, a greater change in plate voltage occurs with a large load resistor than occurs when a small load resistor is used. Thus, within the limitations of the supply voltage, the larger the value of R_L the greater will be the voltage gain.

If the load resistance remains fixed and the power supply voltage is changed, the effect on the load line is as shown in Figure 19-21B. From left to right, the load lines have been constructed for supply voltages of 100, 200, and 300 volts respectively. Each of the three load lines represents an R_L of 20,000 ohms. Notice,

A12. Approximately 15. If the Q point is not changed the gain is relatively constant with small changes in input signal amplitude.

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that reducing the supply voltage from 300 volts to 200 volts does not change the slope of the load line, it merely shifts the entire load line to the left on the family of curves.

Q13. With the bias maintained at -2 volts, compare the change in plate current that occurs as E_{bb} is varied from 300 volts to 200 volts, to the change in plate current that occurs as E_{bb} is varied from 200 volts to 100 volts.

19-13. Dynamic Transfer Characteristic

Under certain circumstances, only the relationship between grid voltage and plate current is of interest. For such an application, it would be of great advantage to have a single curve showing the dependency of plate current on grid voltage. Although the grid family of curves discussed in section 19-5 illustates this very relationship, their use is limited since each curve is a static curve, valid for one value of plate voltage only. The desired curve must be a dynamic curve——one that takes into consideration the fact that the load resistance causes plate voltage to change whenever the grid voltage causes a change in plate current. This curve is a special type of E_c-I_b curve, and is called a DYNAMIC TRANSFER CHARACTERISTIC to distinguish it from the static E_c-I_b curves.

A dynamic transfer characteristic can be obtained by inserting a milliammeter into the plate circuit of the amplifier and then recording the plate currents obtained for various values of grid voltage, or, it can be constructed through the use of a load line drawn on the plate family of curves. The procedure for constructing the transfer characteristic from the plate family of curves will be outlined using Figure 19-22.

To construct the transfer characteristic a load line is drawn on the plate family of curves. Since the circuit has a supply voltage of 300 volts and a load resistance of 20,000 ohms, the load line has X and Y intercepts of (300V, 0 ma) and (0 volts, 15 ma) respectively.

After completing the load line, a grid of horizontal and vertical lines is constructed to the left of the plate family of curves. The horizontal axis of this grid is scaled off in volts and labeled E_c. The vertical axis represents plate current (I_b) and is identical to the vertical axis of the plate family of curves.

The points used to plot the dynamic transfer curve are projected from the points formed by the intersection of the load line and each of the individual plate curves. For example, if the grid voltage is zero the tube operating point is at A, the intersection of the load line and the curve marked $E_c = 0$. Point A represents a grid voltage of zero and a plate current of 10.2 ma. These values of voltage and current are transferred to the graph on the left as point A'. In a similar manner point B and the other remaining points are transferred to the graph on the left. After all of the points have been plotted, the dynamic transfer characteristic is completed by drawing a smooth curve through the plot points.

Notice, that the resulting curve is straight or linear from point A' to about point C'. The section of the curve between point C' and cut-off is called the "lower knee" of the curve and is non-linear. The portion of the curve that the

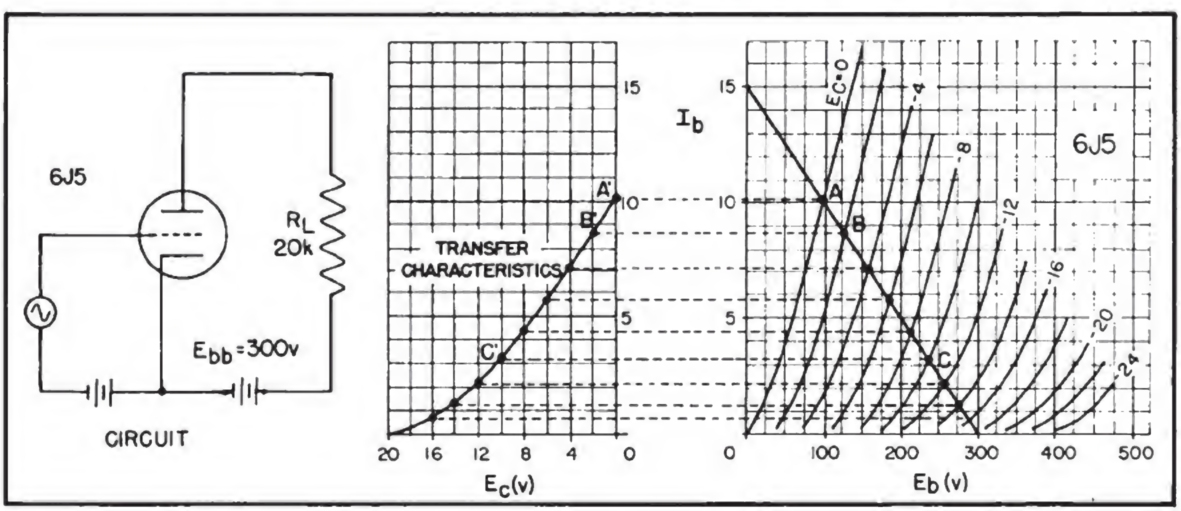

Figure 19-22 - Construction of a dynamic transfer characteristic.

tube actually uses depends on the job the tube is designed to accomplish. Electrically, the area of the curve used is determined by the amount of bias and the amplitude of the input signal. Selection of the correct bias is presented in the following topic.

CLASSES OF OPERATION

The waveform of the signal voltage at the plate of a vacuum tube amplifier depends on the waveform of the signal applied, and the part of the dynamic transfer characteristic that is used. Most audio amplifiers are designed to produce an output waveform that is increased in amplitude but otherwise identical to the input signal. There are cases, however, where distortion is purposely introduced into a signal to achieve special changes in the shape of the waveform.

If faithful reproduction of the signal is desired (high fidelity reproduction), the vacuum tube must be adjusted to operate on the straight or linear section of its characteristic curve. If distortion is desired, the tube is operated on the curved or non-linear part of its characteristic. The section of the curve over which the tube operates is determined by the class of operation, which in turn is determined by the amount of bias applied to the tube. The four classes of operation are A, B, AB, and C.

19-14. Class A Operation

A class A amplifier is defined as an amplifier in which the bias and input signal are adjusted so that plate current flows for the full 360° of the input cycle of signal voltage. According to the definition of class A operation, the tube could be biased at any point along its dynamic transfer characteristic (hereafter referred to as the E_c-I_b curve), and as long as the signal was not large enough to drive the tube into cut-off it would be considered a class A amplifier.

In the majority of applications of class A amplifiers a distortion free output is desired. To achieve this, the bias is adjusted so that with no applied signal the dc operating point is near the center of the linear portion of the E_c-I_b curve. Typical operating conditions for a class A amplifier are shown in Figure 19-23. The bias on this amplifier is -6 volts, placing the no-signal operating point at Q. Thus, with no signal applied to the control grid, approximately 5.8 ma of current flows continuously in the plate circuit of the amplifier.

The input signal applied to the grid of the amplifier is a sine wave having a peak amplitude of 4 volts. This sine wave signal causes the grid voltage to swing 4 volts above and below the bias voltage of -6 volts. The total grid swing is from -2 volts at the peak of the positive alternation to -10 volts at the peak of the negative alternation.

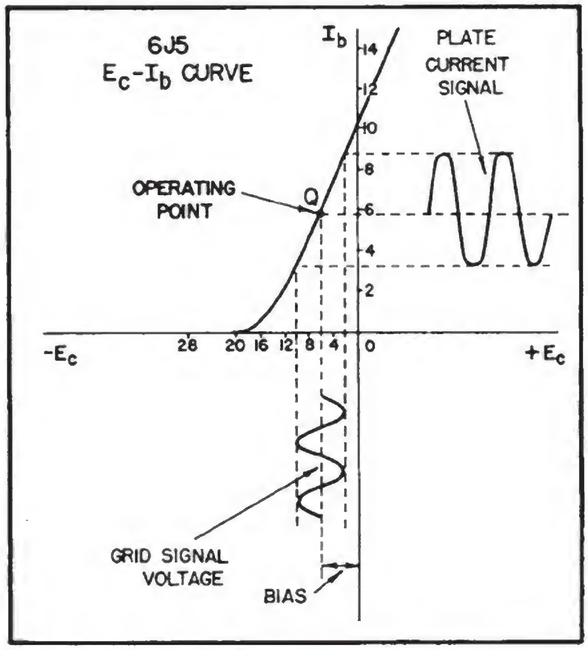

Figure 19-23 - Bias and input signal conditions for a typical class A amplifier.

By projecting the grid signal upward to the E_c-I_b curve and then right to the I_b axis, a graph of the plate current waveform can be constructed. Note, that plate current swings above and below an average value of approximately 5.8 ma. If the E_c-I_b curve was perfectly linear the increase of current on the positive alternation of the grid signal would be exactly equal to the decrease of current on the negative alternation, and the average dc plate current would be the same with or without a signal. In actual practice the positive alternation of plate current will usually be somewhat larger than the negative alternation causing a slight increase in the dc plate current as the signal is applied to the tube. This is a form of distortion caused by the curvature of the E_c-I_b curve and can usually be neglected when the tube is operated on the nearly linear section of the curve.

Although the output signal from a class A amplifier can be made to approach an almost perfect reproduction of the input signal, the efficiency of operation is poor. That is to say, a large amount of power is wasted in the process of amplifying the signal. The PLATE EFFI-

A13. As E_{bb} is changed from 300 to 200 volts I_b decreases from 8.6 ma to 5.1 ma, a change of 3.5 ma. As E_{bb} is changed from 200 to 100 volts I_b decreases from 5.1 ma to 1.7 ma, a change of 3.4 ma. Thus, for this bias, equal changes in E_b produce nearly equal changes in I_b.

CIENCY of an amplifier is the ratio of the ac output power across the load to the dc input power supplied to the plate circuit of the amplifier. The formula for percent of plate circuit efficiency is:

$$\% \text{ EFF} = \frac{P_o}{P_i} \times 100 \qquad (19\text{-}2)$$

where: $\%$ EFF = the plate efficiency in %
P_o = the ac power developed in the load in watts
P_i = the dc input power to the plate of the tube (numerically equal to $E_b \times I_b$)

Equation (19-2) is included at this point solely for the purpose of illustrating the relationship between input power, output power, and efficiency. The efficiency of a practical triode class A amplifier is on the order of 20 to 25 percent.

Grid current does not flow in most class A amplifiers. To show that grid current does not flow during any part of the input cycle, the subscript "1" may be added to the letter or letters of the class identification. The subscript "2" may be used to indicate that grid current flows during some parts of the input cycle. Thus, if the grid is not driven positive at any time in the class A cycle no grid current will flow and the amplifier is designated class A_1. If no subscript is shown with the letter A, it is assumed that no grid current flows.

The principal characteristics of class A amplifiers are minimum distortion, low power output for a given tube (relative to class B and class C amplifiers), high power amplification, and relatively low plate efficiency. This type of amplifier finds wide use in various audio systems where low distortion is important.

19-15. Class B Operation

Class A operation was found to be very inefficient because of the large dc current drawn by the plate circuit of the tube. A considerable improvement in efficiency can be obtained by shifting the operating point down the E_c-I_b curve toward cut-off. This shift in operating point is accomplished by increasing the negative bias

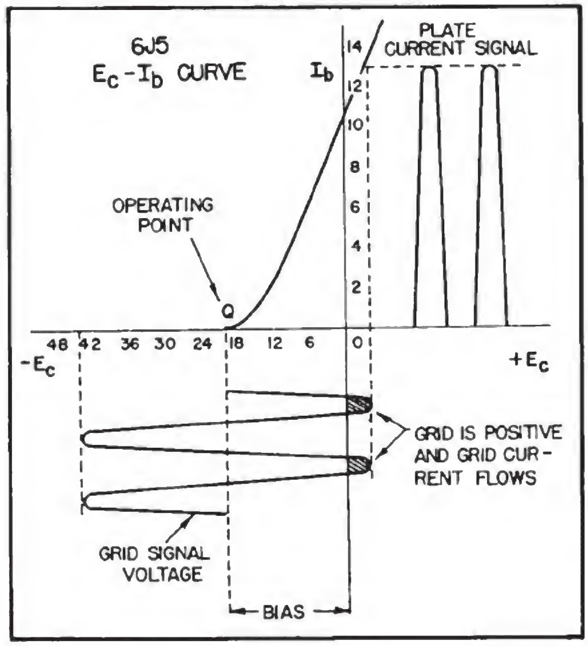

Figure 19-24 - Class B operation.

applied to the grid.

To operate an amplifier class B, the negative grid voltage is increased until the operating point of the tube is biased at or near cut-off, as shown in Figure 19-24. Without an applied signal the plate current is either zero or very low, reducing the power losses of the circuit.

When a signal is applied to the grid of a class B amplifier, plate current will flow for approximately one-half (180°) of each cycle of grid voltage. An examination of Figure 19-24 shows that plate current flows only during the positive alternation of the grid signal, producing an output waveform similar to that obtained from a half-wave rectifier. This severely distorted plate current pulse is rich in harmonic energy generated by the non-linear operation of the tube. Because of this distortion, a single tube operated class B is unsuitable for audio amplification. However, two tubes can be combined in a single stage such that the majority of the distortion is eliminated. This circuit is called a PUSH-PULL amplifier and will be studied in Chapter 22.

In order to obtain the maximum output power from a class B amplifier, a large driving signal must be applied to its grid. As shown in Figure 19-24 this signal is commonly several times greater in amplitude than the signal required for class A operation of the same tube.

Depending on the amplitude of the driving

signal the tube can be operated either class B_1 or class B_2. The amplifier shown in Figure 19-24 is driven into the positive grid region at the peak of each positive alternation and is therefore operating class B_2. For the period of time the grid signal is above the zero axis (shaded area), the grid is positive with respect to the cathode and grid current is drawn. Unless the signal source used to drive the class B amplifier has a low internal impedance (good regulation), the grid current will cause clipping of the positive peaks of the grid signal, thus increasing distortion.

The characteristics of class B amplifiers are medium output power, medium plate efficiency of 40 to 60 percent, large bias voltage, large driving signal requirements, and for a single tube, severe distortion.

19-16. Class AB Operation

Class AB amplifiers have grid biases and input-signal voltages of such values that plate current flows for appreciably more than half the input cycle but for less than the entire cycle, as indicated in Figure 19-25. Class AB operation is essentially a compromise between the low distortion of the class A amplifier and the higher efficiency of the class B amplifier.

If the input signal drives the grid positive with respect to the cathode, grid current will flow during the positive peaks and the amplifier is designated as a class AB_2 amplifier. Although a class AB_2 amplifier delivers slightly more power to its load, the class AB_1 amplifier has the advantage of presenting to its driver a constant impedance. In contrast with this effect the amplifier that draws grid current over a portion of its input cycle presents a changing impedance to its driver at the point where grid current starts to flow. Thus, when grid current flows the impedance falls to a relatively low value. The driver that supplies this kind of load must be designed to supply undistorted power to the load during these periodic intervals of low impedance.

19-17. Class C Operation

Class C amplifiers have biases of from two to five times the cut-off bias; consequently plate current flows for less than half (160° or less) of each cycle of the input signal. Because of the brief period during which the tube conducts, the average current is small compared to the peak plate current and plate efficiencies of 70 to 80 percent are readily obtainable.

Class C amplifiers are not used as audio amplifiers because of the extreme distortion that they produce, but they are used as RF power amplifiers in transmitters, where tank circuits can be employed as plate loads to restore the missing portions of each cycle.

The conditions for class C operation are illustrated in Figure 19-26. Notice, that the operating point is far below cut-off, and that an extremely large grid signal is required to bring the tube into conduction. To drive the tube to full output, the grid signal must be large enough to drive the grid substantially positive at the crest of the positive alternation. Class C RF

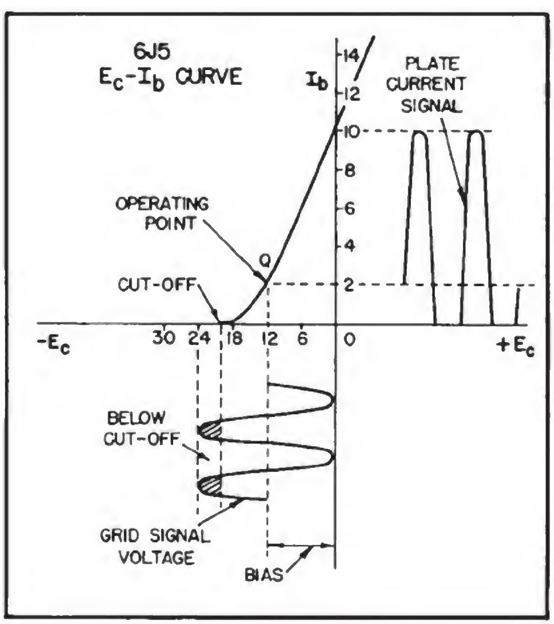

Figure 19-25 - Class AB operation.

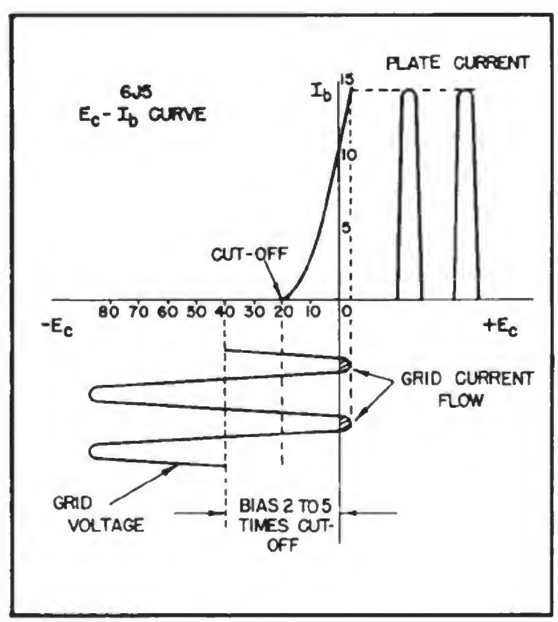

Figure 19-26 - Class C operation.

power amplifiers in which the control grid is driven from 50 to several hundred volts positive are not uncommon. Since grid current is the rule rather than the exception in class C amplifiers, the subscript "2" is usually omitted from the designation.

Q14. Which class of operation should be used if maximum output power is the only consideration?

METHODS OF BIASING

In all amplifier circuits previously discussed, bias has been supplied by a battery, E_{cc}. This type of bias, known as FIXED BIAS, is obtained from a separate voltage source. Power supplies, and dc generators are other examples of fixed-bias supplies. The type of bias most commonly used is CATHODE or SELF-BIAS in which the bias voltage is developed across a resistance by the tube itself. The voltage drop across this resistance is dependent upon the plate current of the tube. COMBINATION BIAS is a combination of fixed bias and self-bias.

19-18. Fixed Bias.

A method of obtaining fixed bias is shown in Figure 19-27. As previously stated, bias is the dc voltage between grid and cathode. This voltage usually is negative, and it is used to establish the operating point. The bias voltage shown in the circuit is -5 volts and is developed by the bias battery. No grid current flows under quiescent conditions since the grid is negative with relation to the cathode. The grid is 5 volts negative with relation to the cathode, or the cathode is 5 volts positive with relation to the grid. Grid resistor R_g provides the dc return path to the cathode. The voltage that appears from grid to ground is equal to the bias voltage plus the instantaneous value of grid signal voltage. In this case the bias is independent of the input grid signal.

19-19. Cathode or Self-bias

The most common method used to obtain bias is CATHODE BIAS (Figure 19-28). In this circuit the bias voltage is developed across cathode resistor R_k. Under quiescent conditions, plate current I_b flows continuously from cathode to plate and back to the cathode through resistor R_k. Since the plate current flows from points A to B, point A is negative in respect to point B. Assume that the voltage drop across R_k equals 5 volts. This makes the cathode 5 volts positive with relation to the grid or the grid 5 volts negative with relation to the cathode.

As explained previously, resistor R_g is part of the dc return path between grid and cathode. If a sinusoidal grid signal is impressed across R_g, it causes the plate current to vary sinusoidally about an average dc value. The varying plate current flows through cathode resistor R_k. Since the required bias is a fixed voltage, the ac component of plate current through resistor R_k must be removed. This is accomplished by capacitor C_k. The value of this capacitor is large so that its capacitive reactance is small compared with the resistance of R_k at the frequency of the input grid signal. This low value of capacitive reactance effectively short-circuits or BYPASSES the ac voltage component around R_k. The result is that the voltage drop across R_k does not vary and the bias voltage remains fixed at -5 volts

The value of C_k in AF amplifiers is approximately 10 to 50 µf (microfarads). In RF amplifiers, it is considerably smaller. Smaller capacitors are used since higher frequencies are involved. The value of R_k is usually from 250 to 3,000 ohms. R_k can be calculated by Ohm's

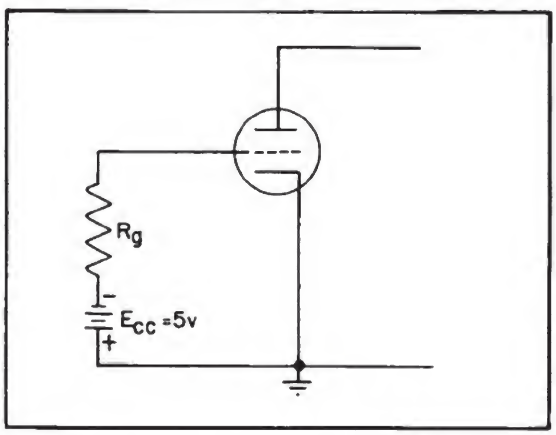

Figure 19-27 - Amplifier showing use of fixed-bias.

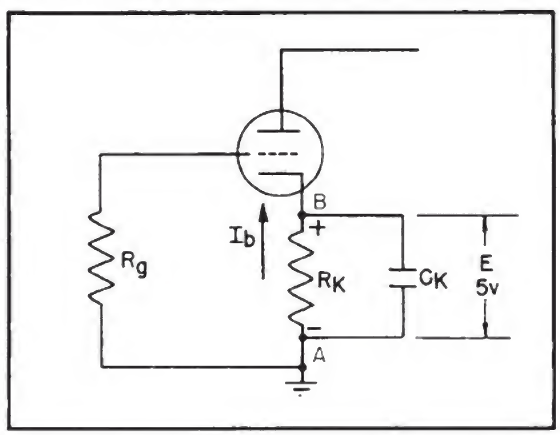

Figure 19-28 - Amplifier showing use of cathode bias.

law if the desired bias and plate current values are known. For example, assume that an average dc plate current of 10 ma flows and that a negative bias of 5 volts is required. Then by Ohm's law:

$$R_k = \frac{E_{cc}}{I_b}$$

$$R_k = \frac{5}{.01}$$

$$R_k = 500 \text{ ohms}$$

The value of the cathode bypass capacitor can be computed by assuming that the reactance of this capacitor should be one-tenth the resistance of the cathode resistor at the lowest frequency to be amplified. By rearranging the equation for capacitive reactance, a formula can be derived for computing the size of C_k.

$$X_c = \frac{1}{2\pi f C} \qquad (10\text{-}24)$$

$$X_c = \frac{1}{\omega C}$$

Solving for C:

$$C = \frac{1}{\omega X_c}$$

Since X_c should equal one-tenth R_k:

$$C_k = \frac{1}{\omega \frac{R_k}{10}}$$

$$C_k = \frac{10}{\omega R_k} \qquad (19\text{-}3)$$

where:

C_k = value of the cathode bypass capacitor in farads

R_k = value of the cathode resistor in ohms

$\omega = 2\pi f$, where f is the lowest frequency in cps to be amplified

Assuming the lowest frequency to be amplified by an amplifier stage having a 500 ohm cathode resistor is 80 cycles per second, the value of the cathode bypass capacitor would be:

$$C_k = \frac{10}{\omega R_k} \qquad (19\text{-}3)$$

$$C_k = \frac{10}{6.28 \times 80 \times 500}$$

$$C_k = 39.8 \text{ microfarads}$$

Since capacitors are manufactured in certain standard values, a standard value equal to or greater than the computed value would be chosen. Normally, the next higher standard value would be used, in this case 40 microfarads.

If the cathode bypass capacitor is omitted, a small voltage variation develops across the cathode bias resistor each time a change occurs in plate current. The polarity of this voltage is such as to oppose the change in plate current. For example, if the input signal makes the grid less negative, plate current will increase. The increase in current will produce a larger bias voltage across the cathode resistor which tends to reduce plate current. Thus, the varying cathode voltage prevents the input signal from producing the full change in plate current, causing a reduction in gain. This process, whereby a signal causes itself to be partially cancelled is called DEGENERATION or NEGATIVE FEEDBACK. Although degenerative feedback causes a loss in amplification, it reduces the distortion introduced into the signal and is often used for this purpose.

19-20. The Cathode Bias Line

When cathode bias is used, the operating point is not so readily identified as when fixed bias is used. In order to locate the operating point along the load line, an additional line is constructed on the family of curves to represent the cathode resistor. The intersection of this line, called the CATHODE BIAS LINE, and the dc load line identifies the operating point. The procedure used to construct a cathode bias line will be demonstrated using an amplifier circuit in which the bias voltage is developed across a 1000 ohm cathode resistor (see Figure 19-29).

The first step in the analysis of this circuit consists of plotting the load line on the plate family of curves. Unlike previous circuits for which load lines have been plotted, the amplifier in Figure 19-29 contains two resistors through which plate current must flow. If extreme accuracy is required, the value of R_k must be included along with R_L in computing the Y-axis intercept of the load line.

In cases where the resistance of the cathode resistor is less than one-tenth the resistance of the plate load resistor, the resistance of the cathode resistor can be neglected in constructing the load line without causing an appreciable error in the results. This policy of neglecting the cathode resistor if it is less than ten percent of the plate load resistor will be adopted here. The load line for the amplifier is shown in Figure 19-29.

To locate the points needed to establish the cathode bias line the value of the bias resistor must be known. Next, two values of voltage are assumed to appear across this resistor, and the

A14. Class C.

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resistor current is calculated for each of the assumed voltages. These two sets of current and voltage values represent two points on the cathode bias line. For example, if the bias is assumed to be -2 volts the current through the cathode resistor would have to be 2 ma. Since the current that flows through the cathode resistor is also the plate current, these current and voltage values can be plotted as point X in Figure 19-29 (E_c = -2, I_b = 2 ma). If the second voltage drop across R_k is assumed to be 8 volts, plate current would be 8 ma and grid voltage would be -8 volts, locating point Y on the graph.

Since point X is below the load line and point Y is above the load line, the operating point must lie on the load line, somewhere between points X and Y. The exact operating point is located by drawing a straight line between points X and Y. This line is the cathode bias line and it intersects the load line at point Q. Thus, the quiescent values in the circuit are: I_b = 4.9 ma, E_b = 155 volts, and E_c = -4.9 volts. Once the operating point has been established, the analysis of the amplifier with an input signal is carried out the same as if the amplifier had fixed bias.

If a cathode bias line is plotted using a large number of points spread out over the graph, the bias line would be found to be slightly curved. In fact, by placing a straight edge along the cathode bias line in Figure 19-29 it can be seen that an extension of the bias line would not pass through the origin of the graph, whereas if plotted accurately the bias line must pass through this point. By choosing two points, one on either side of the load line, the bias line can be established with accuracy sufficient for most purposes.

Q15. What would be the bias voltage on the amplifier in Figure 19-29 if an additional resistance of 1000 ohms is connected in parallel with R_k?

COUPLED AMPLIFIERS

When the gain provided by a single amplifier stage is insufficient, two or more amplifier stages can be connected in CASCADE, as shown in Figure 19-30. In this arrangement the signal is applied to the first amplifier, amplified, and coupled to the second amplifier where it is again amplified. Assuming all three amplifier stages in Figure 19-30 to have a gain (A) of 20, the signal at the output of the first amplifier stage is 20 times larger than the input signal. After amplification by the second stage, the signal is 20 x 20 or 400 times greater than the original input signal. After three stages of amplification

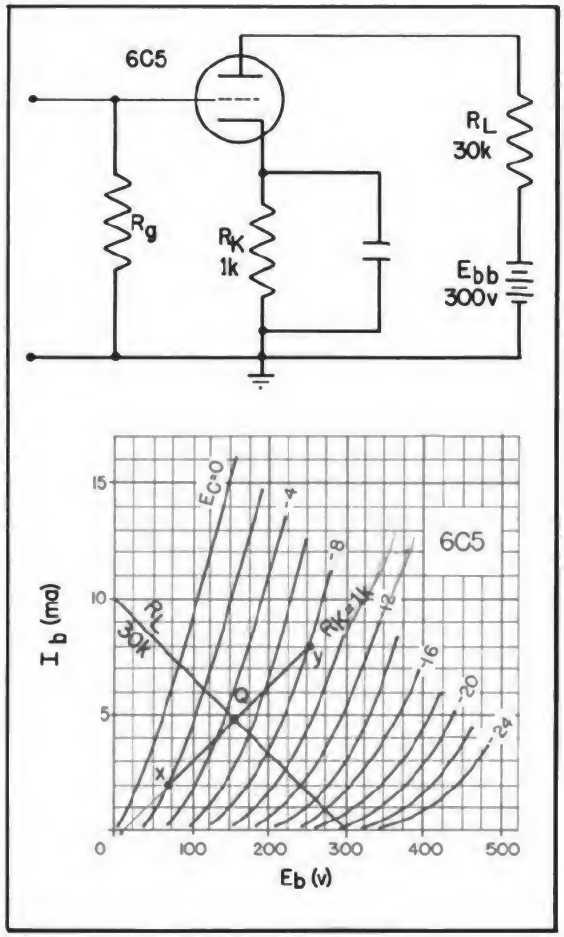

Figure 19-29 - Constructing the cathode bias line.

the total gain is 20 x 20 x 20 or 8000. Notice, that the total gain is the PRODUCT of the individual stage gains.

Cascade amplifiers can be coupled together by one of three methods: DIRECT COUPLING, INDUCTIVE COUPLING, or CAPACITIVE COUPLING. Capacitive coupling can be further sub-divided into RESISTANCE-CAPACITANCE (RC) COUPLING and IMPEDANCE COUPLING.

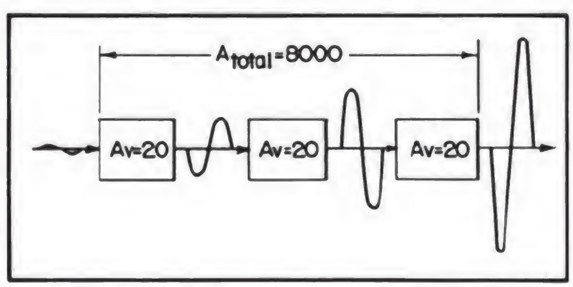

Figure 19-30 - Three stage cascade amplifier.

Q16. What would the peak amplitude of the output signal be, if the input signal to the amplifier in Figure 19-30 was 3 millivolts?

19-21. Direct Coupling

In a direct coupled amplifier, the plate of one tube is connected directly to the grid of the next tube without going through a capacitor, a transformer, or any similar coupling device. This arrangement presents a problem of voltage distribution. Since the plate of a tube must have a positive voltage with respect to its cathode, and the grid of the next tube must have a negative voltage with respect to its cathode, it follows that the two cathodes cannot operate at the same potential. Proper voltage distribution is obtained by connecting each succeeding cathode to a source of voltage more positive than the plate of the preceding tube.

When the tube voltages are properly adjusted to give class A operation, the circuit serves as a distortionless amplifier whose response is uniform over a wide frequency range. This type of amplifier is especially effective at the lower frequencies because the impedance of the coupling elements does not vary with the frequency. Thus a direct-coupled amplifier may be used to amplify very low frequency variations in voltage. Also, because the response is practically instantaneous, this type of coupling is useful for amplifying pulse signals where all distortion caused by the coupling elements must be avoided.

19-22. Transformer Coupling

A transformer coupled stage of amplification (Figure 19-31) has certain advantages over other types of coupling. The voltage amplification of the stage may exceed the amplification of the tube if the transformer has a step-up turns ratio. Direct current isolation of the grid of the next tube is provided without the need for a blocking capacitor; and the dc voltage drop across the load resistor (R_L), which is necessary when RC coupling is used, is avoided. This type of coupling is also used to couple a high impedance source to a low impedance load, or vice versa by choosing a suitable turns ratio.

Transformer coupling has the disadvantages of greater cost, greater space requirement, the necessity for greater shilding, and the possibility of poorer frequency response at the higher and lower frequencies. The voltage gain as a function of frequency throughout the range in question is shown in Figure 19-31. The curve shows that the transformer-coupled voltage amplifier has a relatively high gain and uniform frequency response over the middle range of audio frequencies, but poor response for both low and high audio frequencies.

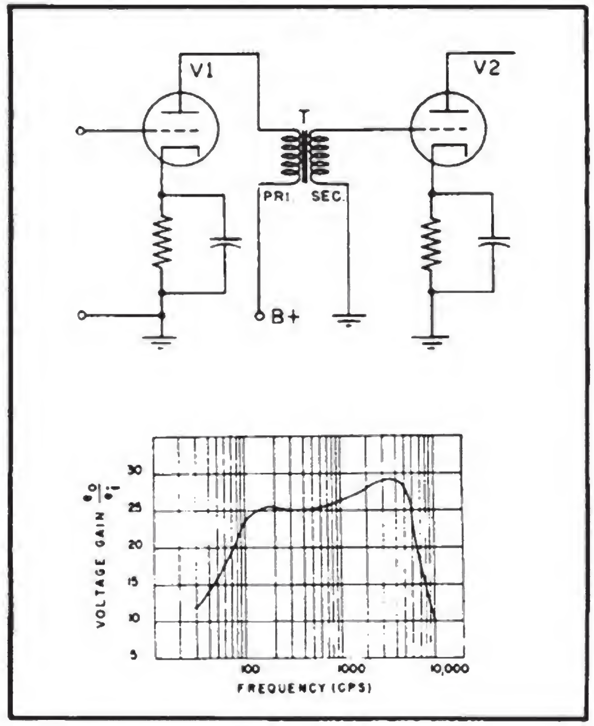

Figure 19-31 - Transformer coupled amplifier and frequency response curve.

19-23. Impedance Coupling

Impedance coupling is obtained by replacing the load resistor, R_L, with an inductance, L, as shown in Figure 19-32. To obtain as much amplification as possible, particularly at the lower frequencies, the inductance is made as large as practicable. To avoid undesirable magnetic coupling a closed-shell type of inductor is used. Because of the low dc resistance of the inductor, less dc voltage appears across it. Thus the tube can operate at a higher plate voltage.

The degree of amplification is not uniform

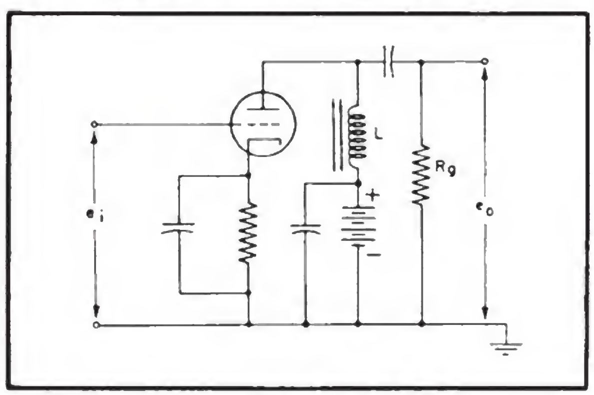

Figure 19-32 - Impedance-coupled amplifier.

A15. Approximately 2.8 volts.

A16. 8000 times 3 millivolts or 24 volts peak.

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because the load impedance, Z_L, varies with the frequency, that is:

$$Z_L = R + j\,2\pi f L$$

Since the output voltage appears across Z_L, the voltage gain increases with the frequency up to the point where the shunting capacitance limits it. The shunting capacitance includes not only the interelectrode and distributed wiring capacitances, but also the distributed capacitance associated with the turns of the inductor. The distributed capacitance between the turns of the coil greatly increases the capacitance to ground, limiting the use of this form of coupling.

19-24. RC Coupling

One of the most widely used methods of connecting amplifier stages is by means of resistance-capacitance (RC) coupling. Amplifiers coupled in this manner are relatively inexpensive, lack heavy components, and have good frequency response. In fact, by special design, RC coupled amplifiers can be made to provide uniform gain for all frequencies within a band several megacycles wide.

A typical RC coupled amplifier circuit is shown in Figure 19-33. Note that each amplifier stage contains the usual components—a grid leak resistor (R_1 and R_g), a plate load resistor (R_L and R_4), and a cathode bias network (R_2C_2 and R_3C_3). A single power supply (E_{bb}) supplies plate voltage to both amplifier stages.

The two amplifier stages are coupled together by connecting capacitor C_c from the plate of V_1 to the grid of V_2. This capacitor, called a COUPLING CAPACITOR, couples the output signal voltage variations from the plate of V_1 to the control grid of V_2 without applying the positive dc plate voltage of V_1 to the grid of V_2. Typical values of coupling capacitors used in vacuum tube audio amplifiers range from about 0.005 microfarad to about 0.25 microfarad, with 0.01 microfarad being one of the most common choices.

19-25. Quiescent Conditions

The quiescent conditions existing in a two stage RC coupled amplifier are relatively unaffected by the addition of a coupling capacitor between the stages. In view of the fact that polystyrene impregnated paper dielectric capacitors have an insulation resistance on the order of 500,000 megohms per microfarad, the capacitor represents an open circuit as far as dc conditions are concerned.

The dc potentials existing in each stage can be determined by constructing load lines and cathode bias lines for each tube. By this method the voltage drops across the various components in stage V_1 have been evaluated and listed for reference on the diagram in Figure 19-33. The dc plate current of 4.4 ma causes a voltage

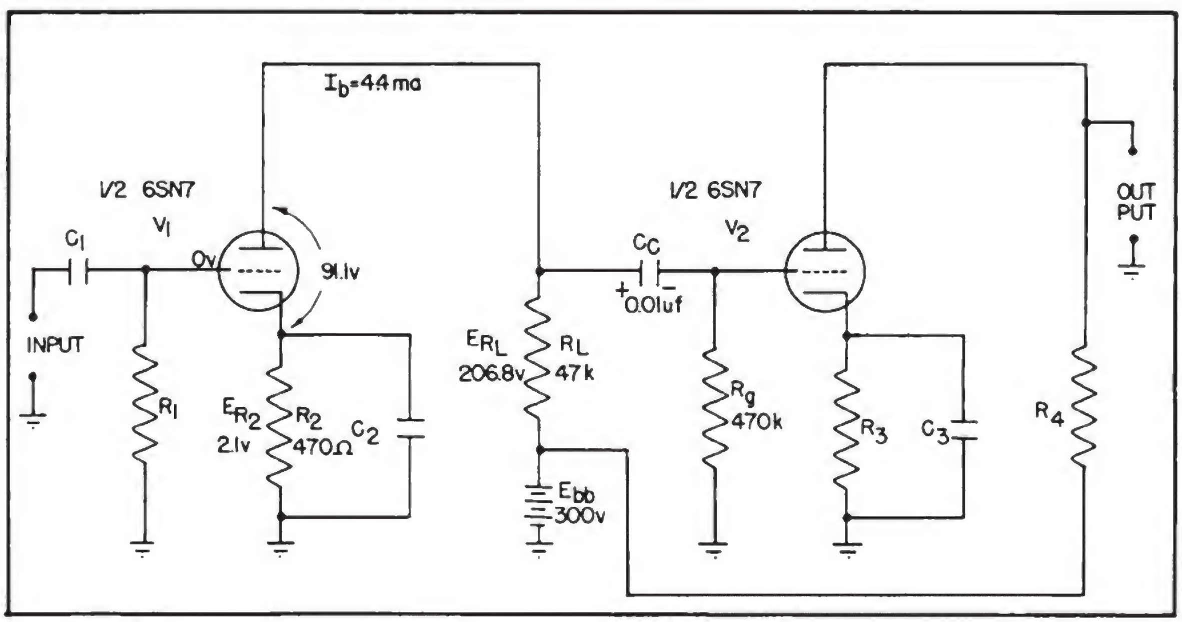

Figure 19-33 - Two stage RC coupled amplifier.

drop across the cathode resistor of approximately 2.1 volts, and a drop across the plate load resistor of 206.8 volts. Deducting the total voltage dropped across the resistors (208.9) from the applied voltage of 300 volts leaves 91.1 volts across the tube. A voltmeter connected between the plate of the tube and chassis ground would indicate 93.2 volts, the sum of the bias voltage E_c (2.1 volts) and the plate voltage E_b (91.1 volts).

The coupling capacitor C_c, in Figure 19-33 connects between points of unequal dc potential. The right side of capacitor C_c connects to the grid end of the grid leak resistor R_g. Since there is no significant dc voltage across R_g, THE RIGHT-HAND PLATE OF C_c IS AT GROUND POTENTIAL. The left side of capacitor C_c is connected to the plate of tube V_1. Thus, THE LEFT-HAND PLATE OF C_c IS AT THE SAME POTENTIAL AS THE PLATE OF TUBE V_1. Inasmuch as the plate of V_1 is at a dc potential of +93.2 volts with respect to chassis ground, capacitor C_c will charge to a potential of 93.2 volts.

The charge path of C_c includes grid leak resistor R_g, plate load resistor R_L, and power supply E_{bb}. When the circuit in Figure 19-33 is first energized electrons leave the negative terminal of E_{bb}, flow through the chassis (ground) to the lower end of R_g, through R_g and into the right-hand plate of C_c making this plate negative. Continuing, electrons leave the left-hand plate of C_c charging it positively, flow downward through R_L to B+, and through E_{bb} to ground completing the circuit. Once charged to 93.2 volts, the capacitor will maintain this average charge until the equipment is deenergized.

Q17. If the insulation resistance of C_c decreased, how would it affect V_2?

19-26. Signal Conditions

To illustrate the operation of the coupling network, assume a one kilocycle sine wave having a peak amplitude of two volts is applied to the grid of V_1 in Figure 19-34, a partial diagram of the amplifier in Figure 19-33. This grid signal causes a sinusoidal variation in plate voltage of approximately 34 volts peak.

At the beginning of the positive alternation, the conditions in the plate circuit of the tube are identical to those which exist under quiescent conditions. That is, the plate-to-ground voltage is 93.2 volts and coupling capacitor C_c is charged to 93.2 volts. No voltage whatsoever appears across grid leak resistor R_g.

During the first 90° of the plate signal, the plate-to-ground voltage rises rapidly to 127.1 volts. Since the voltage from plate to ground is

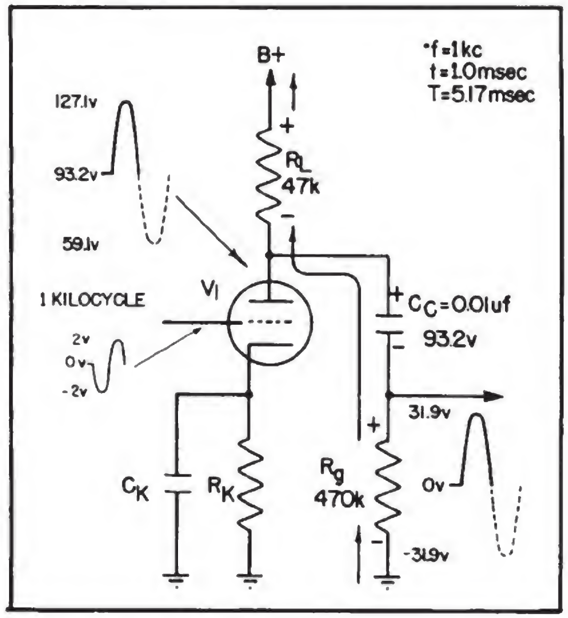

Figure 19-34 - Conditions during the positive alternation of the plate signal.

127.1 volts, and the voltage across C_c is only 93.2 volts, C_c will ATTEMPT to charge an additional 33.9 volts.

The charge path for C_c is designated by the arrows in Figure 19-34. Electrons leave the negative terminal of E_{bb} (ground) and flow up through R_g, C_c, and R_L to the positive terminal of E_{bb} (B+), and then through E_{bb} completing the circuit. Note that in charging, the displacement current of C_c must flow through R_L and R_g.

Since the resistance in series with C_c is large, the time constant for charge is long compared to the period of the sine wave being amplified. The charge time constant of the coupling capacitor (T = RC) is 5.17 milliseconds. A one kilocycle sine wave has a period of one millisecond (t = 1/f), therefore, the first 90° of the plate signal requires 0.25 millisecond. In this brief period of time (five one-hundredths of a single time constant) the capacitor can only begin to charge to the new value of plate voltage. This short period of time limits the charging of the capacitor during the first 90° of the signal to about six percent of the available increase of 33.9 volts, or to an actual increase of about two volts.

As coupling capacitor C_c tries to charge to the new value of plate voltage, its charging current flows through R_g making the top of R_g positive with respect to ground, as shown in

A17. If C_c becomes leaky a direct current will flow upward through R_g, through C_c and R_L to B+, developing a voltage across R_g which opposses the bias on V_2. If the bias is reduced sufficiently distortion can result.

Figure 19-34. According to Kirchhoff's law, the sum of the voltage drops across R_g and C_c must equal the plate-to-ground voltage across the tube. Therefore, since only two volts of the 33.9 volt change in plate voltage appears across the coupling capacitor, the difference between 2 volts and 33.9 volts or 31.9 volts must appear across the resistor. This voltage has the exact same waveform as the plate voltage variations and represents the signal voltage coupled to the grid of V_2. Notice, that due to the long time constant of the coupling network, nearly all of the plate voltage change appears across the grid leak resistor of the following stage, and very little of the signal voltage is dropped across the coupling capacitor.

The conditions existing in stage V_1 during the negative alternation of the plate signal are illustrated in Figure 19-35. As the plate-to-ground voltage swings below the no-signal value of 93.2 volts, coupling capacitor C_c ATTEMPTS to discharge. The discharge displacement current flows down through grid leak resistor R_g, through the cathode bias network and tube to the top plate of C_c, as shown by the arrows in Figure 19-35.

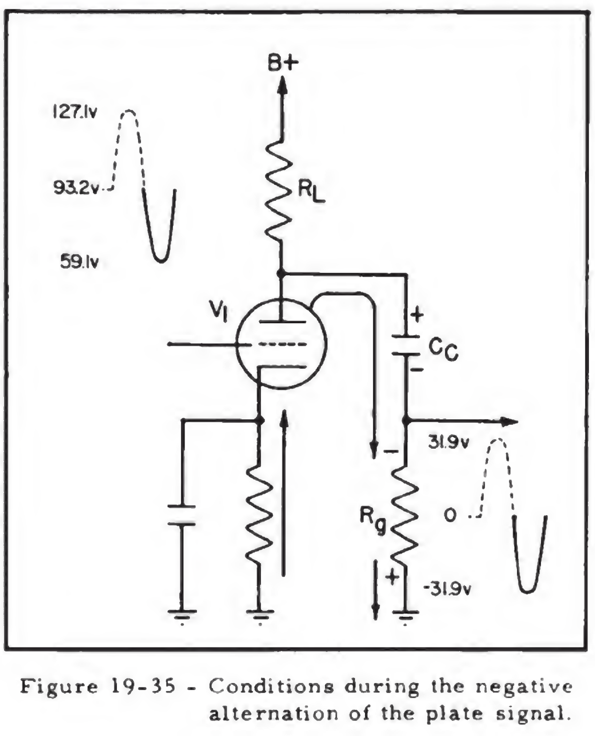

Figure 19-35 - Conditions during the negative alternation of the plate signal.

Notice, that during the negative alternation the current through R_g flows in a direction opposite to the direction of current flow during the positive alternation. Again, due to the long time constant of the coupling network, most of the voltage change appears across R_g and very little appears across C_c. Thus, the ac signal is "coupled" to the grid of the next stage while the dc component of plate voltage is "blocked."

19-27. AC Equivalent Load

When the grid circuit of one amplifier stage is connected to the plate circuit of a preceding amplifier stage by means of a coupling capacitor, the gain of the first stage will be lowered by the loading effect of the grid leak resistor in the following stage. For all but the lowest audio frequencies, the coupling capacitor can be con-

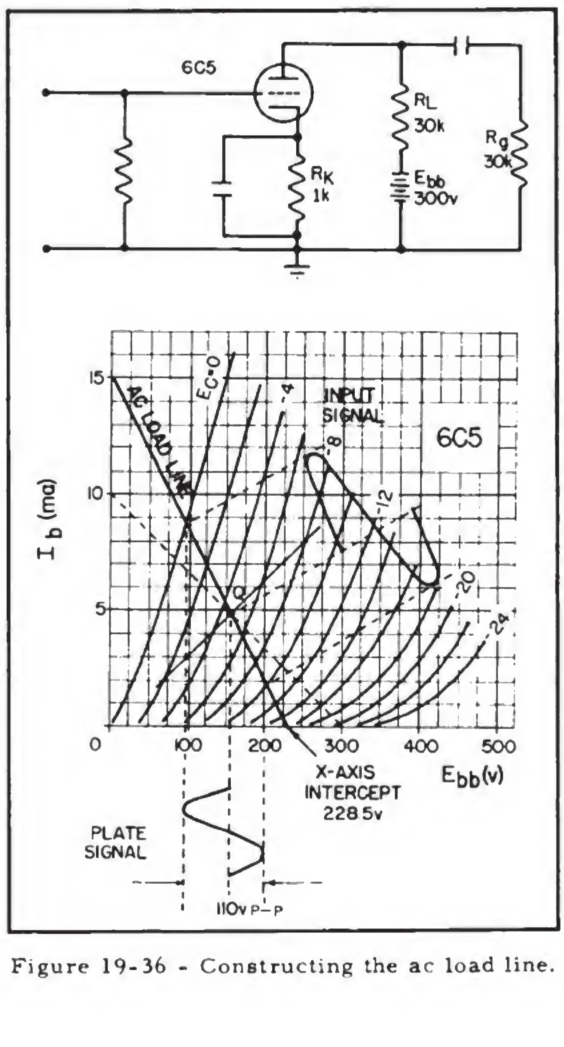

Figure 19-36 - Constructing the ac load line.

sidered as an ac short-circuit, (zero impedance). This places R_g in parallel with R_L (E_{bb} also has zero internal impedance), reducing the load resistance across which the tube develops its output signal. Thus, the dc load line by itself is no longer sufficient to describe the complete operation of the amplifier. The signal voltages and currents are obtained from an AC LOAD LINE.

The ac load line is constructed as a straight line and passes through the same operating point as the dc load line. However, the ac load line represents the equivalent resistance of R_L and R_g and will not have the same slope or X and Y axis intercepts as the dc load line.

To illustrate the construction of an ac load line the circuit and family of curves in Figure 19-36 will be used. In this circuit the value of the grid leak resistance has been made lower than normal to emphasize its effects on the gain of the amplifier.

The analysis of the amplifier is begun by constructing the dc load line (shown dashed) and cathode bias line by the methods outlined previously. The construction of these two lines shows the operating point Q to be at E_b = 155 volts, I_b = 4. 9 ma, and E_c = approximately -5 volts. This operating point must lie on both ac and dc load lines.

Looking again at Figure 19-36, it is seen that the AC LOAD IMPEDANCE is equal to the equivalent resistance of R_L and R_g in parallel or:

$$Z_L = \frac{R_L R_g}{R_L + R_g}$$

In Figure 19-36 Z_L is 15,000 ohms. The ac load line must, therefore, have a slope of -1/15,000 and pass through operating point Q. A second point on the ac load line can be established by locating the point at which the ac load line intercepts the plate voltage axis. Mathematically, the plate voltage axis intercept is:

$$\text{X-axis intercept} = E_{bo} + (I_{bo} \times Z_L) \quad (19\text{-}4)$$

where: E_{bo} = quiescent plate voltage
I_{bo} = quiescent plate current
Z_L = ac load impedance

For Figure 19-36 the X-axis intercept is:

$$\text{X-axis int.} = 155 + (4.9 \times 10^{-3} \times 15 \times 10^{3})$$
$$\text{X-axis int.} = 228.5 \text{ volts}$$

The ac load line is completed by drawing a line from the X-axis intercept of 228. 5, through the operating point Q as shown in Figure 19-36.

If a peak-to-peak signal of 10 volts is applied to the grid, the plate voltage swing, as found from the ac load line, is 110 volts peak-to-peak. This shows the stage gain to be 11. Contrast this gain of 11 with the gain that would be obtained by disconnecting the coupling capacitor. With the coupling capacitor disconnected the output signal and gain would be obtained from the dc load line. With C_c disconnected the output signal would be 140 volts peak-to-peak and the gain would be 14—considerably more than was obtained with the coupling capacitor connected.

Q18. How would an increase in the value of R_g affect the voltage gain of the preceding stage?

TUBE PARAMETERS

Although graphical methods yield much information about amplifier performance, they have serious limitations where small signals or reactive load circuits are encountered. If the input signal amplitude is in the millivolt or microvolt range, graphical analysis becomes wholly inadequate. Reactive loads produce elliptical load lines which are difficult to analyze.

An alternate approach to the study of amplifier circuits is to develop equations from which the magnitude of the output voltage and the stage gain can be computed. In order to derive and use these equations, special quantities called TUBE PARAMETERS or TUBE CONSTANTS must be known.

In most cases the tube parameters can be found in a tube manual. However, in circuits where the operating conditions are substantially different from the sample conditions listed in the manual, the parameters must be obtained from a family of curves. The three principal tube parameters associated with a triode electron tube are; the AMPLIFICATION FACTOR μ (pronounced mu), the AC PLATE RESISTANCE r_p (sometimes called the dynamic plate resistance, or plate impedance), and the TRANSCONDUCTANCE (formerly called mutual conductance) designated by the symbol gm.

19-28. Amplification Factor

The amplification factor of a tube is a static parameter which indicates the maximum theoretical gain of which the tube is capable. Due to loss factors to be explained later, the actual gain of an RC coupled amplifier can approach, but never attain a gain equal to the amplification factor of the tube. Triodes have amplification factors ranging from 3 to 100.

The amplification factor of an electron tube is actually a comparison of the control that the grid has over plate current, to the control that the plate has over plate current. Stated in the

A18. The gain of the preceding stage would increase.

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form of an equation:

$$\mu = \frac{\Delta E_b}{\Delta E_c}\Bigg|_{\Delta I_b = 0} \qquad (19\text{-}5)$$

where: μ = the amplification factor
ΔI_b = the change in plate current
ΔE_b = a small change in plate voltage
ΔE_c = a small change in grid voltage

Equation (19-5) shows that the μ is obtained by dividing a small change in plate voltage, by the small change in grid voltage required to just counter-balance the effects of the plate voltage change on plate current.

To explain how the amplification factor is obtained from the plate family of curves, assume the tube is to be operated in the vicinity of E_c = 3 volts, I_b = 7 ma, and that the μ is desired for this operating point (see Figure 19-37). According to equation (19-5) a small change in plate voltage must be obtained. A convenient point close to the operating point is selected, and the coordinates for this point (point B) are recorded. The coordinates for point B are; E_b = 110 volts, E_c = -2 volts. Without changing plate current (ΔI_b = 0) the plate voltage is increased to 150 volts at point C. The coordinates of point C are; E_b = 150 volts, E_c = -4 volts. This procedure shows that if plate voltage is increased from 110 volts to 150 volts (ΔE_b = 40 volts) and at the same time grid voltage is adjusted from -2 volts to -4 volts (ΔE_c = 2 volts), that plate current will remain constant at 6 ma (ΔI_b = 0). Inserting these values into equation (19-5):

$$\mu = \frac{\Delta E_b}{\Delta E_c}\Bigg|_{\Delta I_b = 0} \qquad (19\text{-}5)$$

$$\mu = \frac{40}{2}$$

$$\mu = 20$$

The μ is found to be 20 indicating that the grid voltage is 20 times more effective in controlling plate current than is the plate voltage. Since μ is a ratio between two voltages it is a pure number and has no units.

Although the amplification factor of a triode is determined mainly by the physical dimensions of the tube structure, it does vary to a small degree with the amount of current flow through the tube. In general, the higher the current the higher will be the amplification factor.

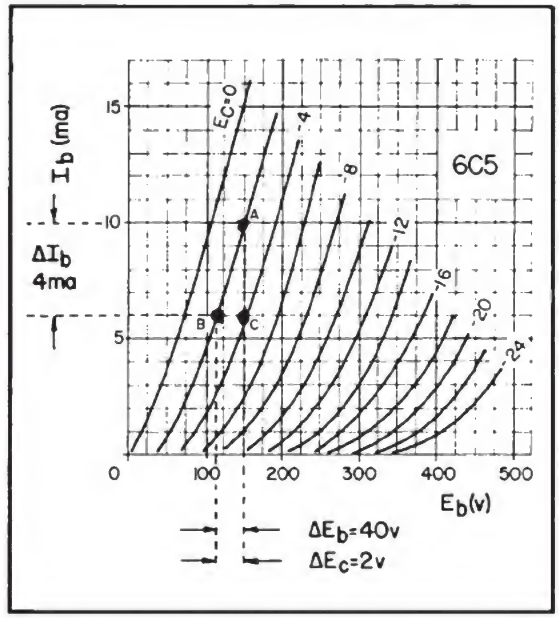

Figure 19-37 - Obtaining tube parameters from the plate family of curves.

Q19. What change in grid voltage would be required to offset a 40 volt increase in plate voltage if the tube had a μ of 100?

19-29. AC Plate Resistance

The ac or dynamic plate resistance (r_p) is a measure of the opposition the tube presents to a changing plate current. In order to obtain the r_p of a tube from its plate family of curves, the grid voltage must be held constant while changes in plate voltage and plate current are acquired. The r_p is computed using equation (19-6).

$$r_p = \frac{\Delta E_b}{\Delta I_b}\Bigg|_{\Delta E_c = 0} \qquad (19\text{-}6)$$

where: r_p = the ac plate resistance in ohms
ΔE_b = a small change in plate voltage
ΔI_b = the change in I_b resulting from ΔE_b
ΔE_c = the change in grid voltage

To obtain the information required for equation (19-6) assume the tube is operating at point B in Figure 19-37. The coordinates of this point are; E_b = 110 volts, I_b = 6 ma, E_c = -2 volts. If the plate voltage is increased to 150 volts while maintaining the same grid voltage, the operating point will shift to point A. The coordinates for point A are; E_b = 150 volts, I_b = 10 ma, E_c = -2 volts. Note that in shifting the

operating point from B to A plate voltage has changed 40 volts, plate current has changed 4 ma, and grid voltage has remained at -2 volts. Inserting these values into equation (19-6):

$$r_p = \frac{\Delta E_b}{\Delta I_b} \Bigg| \Delta E_c = 0 \qquad (19\text{-}6)$$

$$r_p = \frac{40}{4 \times 10^{-3}}$$

$$r_p = 10,000 \text{ ohms}$$

Thus, the ac plate resistance in the vicinity of points A and B is 10,000 ohms. Compare this to the dc resistance obtained at either point A (15,000 ohms), or point B (18,300 ohms).

Like the amplification factor of a tube, the plate resistance is not constant but depends on the operating point of the tube. At low values of plate current the plate resistance is high, while for high values of plate current the plate resistance is considerably lower. Triode plate resistances range from less than 1,000 ohms (2A3) to over 100,000 ohms (6SQ7). In general, low-mu triodes have low plate resistances and high-mu triodes have high plate resistances.

Q20. Compute the r_p of a 6C5 for a bias of -14 volts and a plate voltage change of from 250 to 275 volts. Compare the r_p for this area of the curves to the r_p obtained in the vicinity of points A and B.

19-30. Transconductance

Whereas plate resistance opposes the flow of plate current, conductance is a measure of the ease with which current can flow. The transconductance of a triode is sometimes referred to as the grid-to-plate transconductance, indicating that transconductance is a measure of the ability of a small change in grid voltage to produce a relatively large change in plate current. Mathematically transconductance is:

$$gm = \frac{\Delta I_b}{\Delta E_c} \Bigg| \Delta E_b = 0 \qquad (19\text{-}7)$$

where: gm = the grid-to-plate transconductance
ΔE_c = a small change in grid voltage
ΔI_b = the change in I_b resulting from ΔE_c
ΔE_b = the change in plate voltage

The conductance of a circuit is normally measured in mhos. The mho, however, is an inconveniently large unit when applied to vacuum tube conductances. Thus, the transconductance of a vacuum tube is normally given in micromhos. In using equation (19-7) the transconductance will be in mhos if I_b is in amperes and E_c is in volts. After obtaining the solution the answer is converted to micromhos.

To illustrate the application of equation (19-7) the transconductance will be determined from the curves in Figure 19-37. Assuming the operating point is initially at C, the coordinates for this point are; E_b = 150 volts, I_b = 6 ma, E_c = -4 volts. If the operating point is shifted to point A the new coordinates will be; E_b = 150 volts (ΔE_b = 0), I_b = 10 ma (ΔI_b = 4 ma), and E_c = -2 volts (ΔE_c = 2 volts. Inserting the proper quantities into equation (19-7):

$$gm = \frac{\Delta I_b}{\Delta E_c} \Bigg| \Delta E_b = 0 \qquad (19\text{-}7)$$

$$gm = \frac{4 \times 10^{-3}}{2}$$

$$gm = 0.002 \text{ mhos}$$

$$gm = 2000 \text{ micromhos}$$

As might be expected the transconductance of an electron tube is not an absolute constant, but varies with the choice of operating points. Since none of the three tube constants are truly constant it is necessary to first locate the desired operating point. The three tube parameters μ, gm, and r_p are then computed using small changes of voltage and current in the area of the curves close to the operating point. It is then assumed that the tube parameters remain relatively constant as long as tube operation is confined to an area of the curves near the area used to compute the tube parameters.

It should not be surprising to learn that a definite relationship exists between the three tube parameters. For example, it has been shown that:

$$gm = \frac{\Delta I_b}{\Delta E_c} \Bigg| \Delta E_b = 0 \qquad (19\text{-}7)$$

and that:

$$r_p = \frac{\Delta E_b}{\Delta I_b} \Bigg| \Delta E_c = 0 \qquad (19\text{-}6)$$

If the right side of equation (19-7) is multiplied by the right side of equation (19-6) the result is:

$$\frac{\Delta I_b}{\Delta E_c} \times \frac{\Delta E_b}{\Delta I_b} = \frac{\Delta E_b}{\Delta E_c}$$

which is equal to μ (equation 19-5). Thus:

$$\mu = gm \, r_p \qquad (19\text{-}8)$$

where: μ = the amplification factor of the tube
gm = the transconductance in mhos
r_p = the plate resistance in ohms

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A19. The grid would have to be made 0.4 volts more negative.

A20. The r_p is about 27,000 ohms, over two and one-half times as large as in the vicinity of points A and B.

Equation (19-8) can be transposed into the following two forms:

$$gm = \frac{\mu}{r_p} \qquad (19\text{-}9)$$

and:

$$r_p = \frac{\mu}{gm} \qquad (19\text{-}10)$$

Q21. What is the transconductance of a tube that has an amplification factor of 100 and a plate resistance of 80,000 ohms?

VACUUM TUBE EQUIVALENT CIRCUIT

Frequently it is more convenient to work with an equivalent circuit than with the original circuit. Since in most cases, only the signal currents and voltages in an amplifier are of interest, the circuit can be greatly simplified by developing an equivalent circuit which includes only those quantities affecting the signal. The equivalent circuit can be developed through the application of either Thevenin's theorem or Norton's theorem. Those desiring a review of Thevenin's and Norton's equivalent circuits are directed to sections 7-18 and 7-21 respectively.

19-31. Thevenin's Equivalent Circuit

According to Thevenin's theorem, any linear network of generators and impedances can be replaced, so far as the load is concerned, by a single generator and a series impedance, wherein the generator voltage is equal to the voltage existing between the load terminals with the load disconnected, and the series impedance is equal to the impedance seen looking back into the load terminals after all generators within the network have been replaced with their internal impedances. Keeping in mind that the equivalent circuit applies to SIGNAL VOLTAGES AND CURRENTS ONLY, and NOT TO DIRECT VOLTAGES AND CURRENTS, the Thevenin's equivalent circuit will be developed for the amplifier in Figure 19-38A.

When a signal is applied to the control grid of a triode vacuum tube, variations are created in the flow of plate current. If the tube is operated properly, the waveform of these current variations will be nearly identical to the original grid signal voltage. Looking back into the amplifier circuit from the load resistor terminals this signal current appears to be supplied to the load resistance by the tube, although in reality, the current is caused by E_{bb} and is only controlled by the tube. Since the signal current appears to be supplied by the tube, the tube and power supply E_{bb} can be replaced by a generator capable of supplying the same signal current as appears to be supplied by the tube.

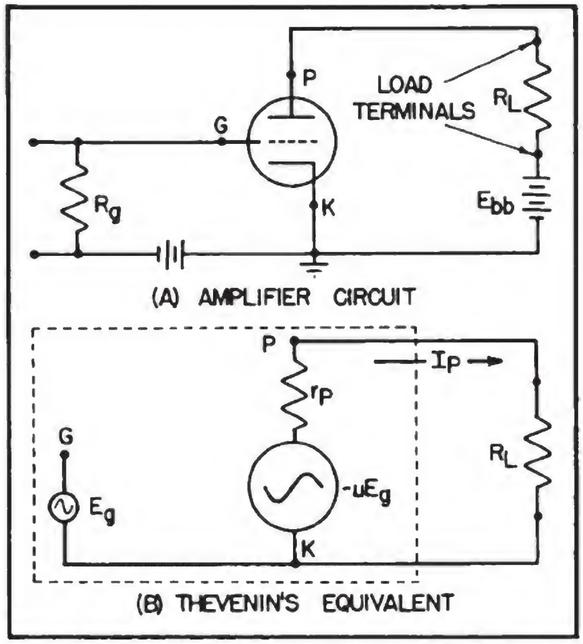

Figure 19-38 - Vacuum tube amplifier and Thevenin's equivalent circuit.

As the signal current flows through the tube it must also flow through the plate resistance of the tube. This makes it necessary to include the ac plate resistance (r_p) in the equivalent circuit for the vacuum tube. The complete equivalent circuit for the tube is made up of the components enclosed by the dashed line in Figure 19-38B. The generator and series resistance (r_p) are connected between the plate terminal (P) and the cathode terminal (K) of the equivalent circuit. The control grid and input signal voltage are represented by terminal (G) and voltage E_g respectively. The entire equivalent circuit is completed by connecting load resistor R_L to terminals (P) and (K) representing the plate and cathode of the tube.

To facilitate circuit analysis it is more convenient to know the generator voltage than the generator current. If the vacuum tube could be

considered as a perfect device, the signal developed at the plate of the tube would be mu times as large as the signal (E_g) applied to the grid. Thus, if the losses within the tube are not considered, the tube acts as a generator whose output voltage can be written as μE_g.

In the equivalent circuit all the losses of the tube are assumed to occur in a resistance (r_p) connected in series with a perfect generator. Since the generator has no losses its output voltage is μE_g. To show that the signal at the output of the generator (plate of the tube) is inverted with respect to the input signal a minus sign is often used in front of the generator voltage as shown in Figure 19-38B. It should also be noted that the voltages and currents used in the equivalent circuit represent RMS values.

Q22. Why is E_{bb} not included in the Thevenin's equivalent circuit of a triode amplifier?

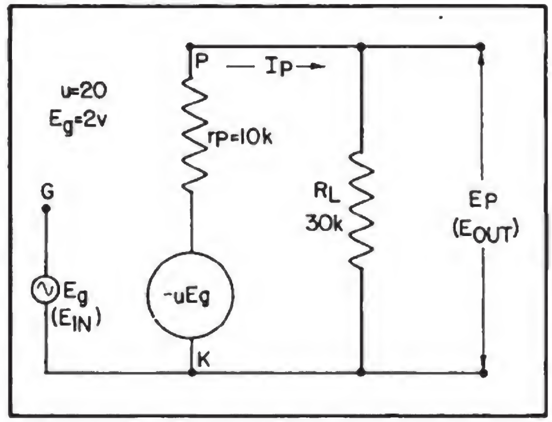

Figure 19-39 - Thevenin's equivalent circuit for 6C5 amplifier.

19-32. Triode Gain Formula

Once an amplifier stage has been reduced to its equivalent circuit it can be readily solved by the application of Ohm's law. Since the equivalent circuit consists of two series resistances, the total resistance is equal to their sum or:

$$R_t = r_p + R_L$$

To compute the ac plate current (I_p), the applied voltage (μE_g) is divided by the total resistance of the circuit.

$$I_p = \frac{\mu E_g}{r_p + R_L} \qquad (19\text{-}11)$$

The application of equation (19-11) can be demonstrated by using it to compute the ac plate current in the equivalent circuit shown in Figure 19-39. This equivalent circuit represents a single amplifier stage containing a 6C5 triode using a plate load resistor of 30,000 ohms. Since the tube has an amplification factor of 20 and an input signal of 2 volts, the generator voltage μE_g in the equivalent circuit is 2 times 20 or 40 volts. Inserting the values into equation (19-11) and solving for plate current I_p:

$$I_p = \frac{20 \times 2}{(10 \times 10^3) + (30 \times 10^3)}$$

$$I_p = 1 \text{ ma}$$

Again it must be pointed out that this one milliampere of plate current represents the alternating or signal component of plate current and is not the dc plate current.

Since the equivalent circuit in Figure 19-39 is a series circuit, the same plate current of one milliampere flows through each part of the circuit. The output voltage (E_p) is the voltage developed across plate load resistance (R_L) by the flow of plate current (I_p). Thus:

$$E_p = I_p R_L \qquad (19\text{-}12)$$

Solving for E_p:

$$E_p = (1 \times 10^{-3})(30 \times 10^3)$$

$$E_p = 30 \text{ volts}$$

If this RMS output voltage of 30 volts is converted to a peak-to-peak value, and then compared to the value of output voltage obtained from a load line, the two methods would be found to give nearly identical results.

By a small amount of algebraic manipulation, a general formula for the gain of an amplifier stage can now be derived. In a previous section the gain of an amplifier was found to be:

$$A_v = \frac{E_o}{E_i} \qquad (19\text{-}1)$$

Since $E_i = E_g$ and $E_o = E_p$

$$A_v = \frac{E_p}{E_g} \qquad (19\text{-}13)$$

Equation (19-12) states: $E_p = I_p R_L$. Thus:

$$A_v = \frac{I_p R_L}{E_g} \qquad (19\text{-}14)$$

However, equation (19-11) states:

$$I_p = \frac{\mu E_g}{r_p + R_L} \qquad (19\text{-}11)$$

A21. $gm = \frac{\mu}{r_p} = \frac{100}{80 \times 10^3} = 1250$ micromhos

A22. The equivalent circuit contains only those components which act as alternating current sources or impedances.

Therefore, by substitution of (19-11) into (19-14):

$$A_v = \frac{\frac{\mu E_g}{r_p + R_L} \times R_L}{E_g}$$

Simplifying:

$$A_v = \frac{\mu E_g R_L}{r_p + R_L} \times \frac{1}{E_g}$$

$$A_v = \frac{\mu R_L}{r_p + R_L} \qquad (19\text{-}15)$$

Equation (19-15) is an important formula for the gain of a triode amplifier. Using this equation, the gain of the amplifier in Figure 19-39 is:

$$A_v = \frac{\mu R_L}{r_p + R_L} \qquad (19\text{-}15)$$

$$A_v = \frac{20 \times 30 \times 10^3}{(10 \times 10^3) + (30 \times 10^3)}$$

$$A_v = 15$$

Q23. By carefully considering the Thevenin's equivalent circuit and the triode gain formula, describe the effect that the value of r_p has on the gain of an amplifier.

AMPLIFIER FREQUENCY RESPONSE

One of the most important characteristics of an amplifier is the way in which it responds to the various frequencies that may be contained in its input signal. The audio frequency spectrum extends from 20 cycles to 20,000 cycles per second. An amplifier which is designed to amplify this band of frequencies should provide the same gain for each different frequency, regardless of its location within the frequency spectrum. The way in which an amplifier responds to each different frequency it is called upon to amplify is called the FREQUENCY RESPONSE characteristics of the amplifier. These characteristics are normally presented in the form of a curve which shows the output voltage or gain as a function of frequency. This curve is called a FREQUENCY RESPONSE CURVE.

Were it not for the inductive and capacitive reactances present in every circuit, an amplifier could be constructed to have perfect frequency response. This is impossible, however, since all circuits contain some reactance. In an RC coupled audio amplifier, most of the reactance is capacitive, and is contained in both the electron tube and the coupling network.

19-33. Interelectrode Capacitance

Capacitance exists between any two metal surfaces separated by a dielectric. The amount of capacitance depends upon the area of the metal surfaces, the distance between them, and the type of dielectric. The electrodes of an electron tube produce a similar characteristic, known as INTERELECTRODE CAPACITANCE, which is illustrated schematically in Figure 19-40. The capacitances that exist in a triode are the grid-to-cathode capacitance C_{gk}, the grid-to-plate capacitance C_{gp}, and the plate-to-cathode capacitance C_{pk}.

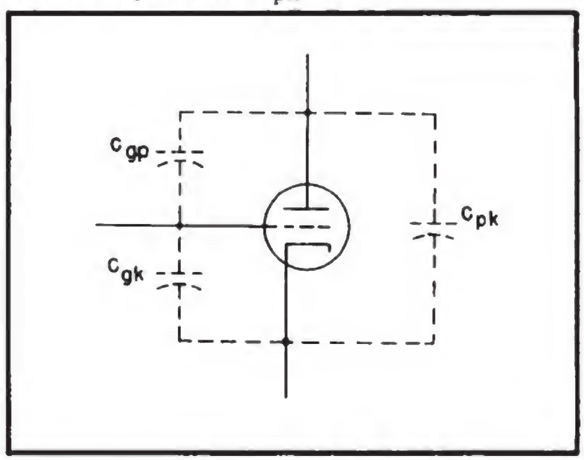

Figure 19-40 - Interelectrode capacitance.

The shunting effect of the interelectrode capacitance of a tube is increased when the electrodes are connected to a circuit having grid, plate, and cathode leads of appreciable length. The capacitance is increased because of the increase in area afforded by the conducting surfaces comprising the circuit wiring, tube bases, sockets, and so forth.

At low and medium frequencies the interelectrode capacitances, as well as the distributed capacitances due to circuit wiring, have only a slight shunting effect because the reactance at these frequencies is high compared with that of other circuit components.

At high frequencies the interelectrode and distributed capacitances cause appreciable shunting effect because of the reduced reactance offered at these frequencies. Also the grid-to-

plate capacitance can feed back some of the plate signal voltage in the proper phase with respect to the grid signal voltage to cause undesired oscillations.

At ultrahigh frequencies (UHF) interelectrode capacitance becomes very objectionable and prevents the use of ordinary electron tubes. Special UHF tubes are used at such operating frequencies. These are characterized by tube elements having very small physical dimensions and closely spaced electrodes that often do not terminate in conventional tube bases.

19-34. Amplifier Response Curve

A partial schematic diagram of a two-stage RC coupled amplifier is shown in Figure 19-41. In addition to the components which normally appear on the schematic diagram of an audio amplifier, three capacitances C_o, C_d, and C_i are shown. These three capacitances are not capacitors in the usual sense of the term, but are made up of the interelectrode and stray wiring capacitance. C_o represents the output capacitance of V_1 and can be considered to be equal to the plate to cathode capacitance of the tube. C_d represents the capacitance distributed throughout the amplifier between the wiring and the chassis. C_i is the input capacitance to the grid of V_2. Because of the influence of the plate circuit on the charge distribution in the grid-cathode circuit, the input capacitance of a triode tube during operation can be many times the cold input capacitance measured with the tube out of the circuit. The apparent input capacitance (C_i) can be closely approximated by equation (19-16):

$$C_i = C_{gk} + C_{gp} (1 + A) \qquad (19\text{-}16)$$

Notice, that C_i does not depend on C_{gk} alone, but is a function of C_{gp} and the stage gain(A) as well. The dependency of the input capacitance on the gain of the amplifier is called the MILLER EFFECT.

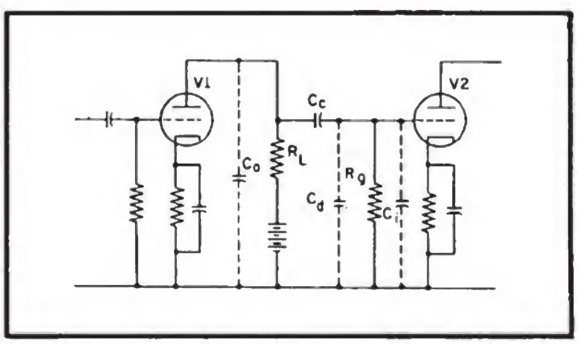

Figure 19- 41- Two-stage RC coupled amplifier.

To illustrate the significance of the Miller effect, assume a 6SQ7 having a grid-to-cathode capacitance of 3.2 pf, and a grid-to-plate capacitance of 1.6 pf, is used as an amplifier in a stage having a gain of 50. The apparent input capacitance would be:

$$C_i = 3.2 + 1.6 (1 + 50)$$

$$C_i = 84.8 \text{ pf}$$

This capacitance is approximately 26.5 times the grid-to-cathode capacitance considered separately.

A frequency response curve for an amplifier can be obtained experimentally if the circuit is accessible, or can be calculated if nothing other than a schematic diagram is available. In either case, the data for the response curve is compiled by applying a series of frequencies, one at a time, to the input terminals of the amplifier and then determining the output voltage. By adjusting each separate input frequency to the same amplitude, a constant reference is established and the amplitude of the output signal depends only on the gain of the amplifier. Either the gain or the output voltage is then plotted as a function of frequency to obtain the response curve for the amplifier.

A response curve for a typical RC coupled audio amplifier is shown in Figure 19-42. This curve shows amplitude varies to a considerable degree with the frequency applied to the amplifier. However, for those frequencies near the center of the band the gain is maximum and nearly uniform.

As the frequency of the signal applied to the amplifier is decreased, less output voltage is obtained, indicating that the gain of the amplifier is reduced. At some low frequency the output

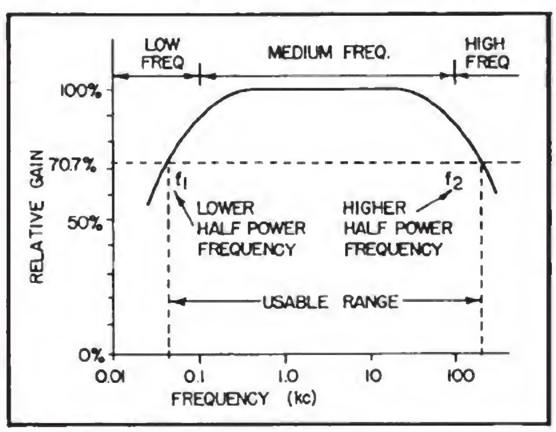

Figure 19-42 - Response curve for RC coupled amplifier.

A23. The equivalent circuit shows that r_p and R_L form a voltage divider across the generator. Thus, the larger r_p becomes, other factors constant, the lower will be the gain and output voltage. This is verified by equation (19-15).

voltage from the amplifier will drop to 70.7 percent of its midband value, causing the output power to decrease to one-half of that available at midband. This frequency is called the LOWER HALF-POWER FREQUENCY or lower cut-off frequency and is designated as (f_1) in Figure 19-42.

The loss of gain at low audio frequencies is a result of the frequency discriminating characteristics of the coupling network. As the applied frequency is decreased the reactance of the coupling capacitor increases. Since the coupling capacitor and the grid leak resistor form an ac voltage divider across the output of the tube, any increase in the reactance of the coupling capacitor causes more of the signal voltage to develop across the coupling capacitor and less to appear across the grid leak resistor of the following stage. Thus, for good low frequency response a large value of coupling capacitor is desirable.

An additional factor which affects the low frequency response of an amplifier is the cathode bypass capacitor. At low frequencies the reactance of the bypass capacitor increases, raising the impedance of the cathode bias network. The increased impedance develops a larger voltage variation across the cathode bias network. Since this voltage variation is a form of degenerative feedback, the gain is reduced at those frequencies for which bypassing is insufficient.

An examination of the right-hand side of the response curve in Figure 19-42 shows that the gain of the amplifier is reduced at the high frequency end of the spectrum as well as the low frequency end. Loss of gain at the higher audio frequencies is brought about by the shunting effect of the interelectrode and wiring capacitance which, electrically, appear in parallel with the plate load resistance and grid leak resistance. The coupling capacitor and cathode bypass capacitor can be neglected at these frequencies due to their low reactance. As the frequency of the signal applied to the amplifier is increased the reactance of this shunt capacitance becomes very low and effectively short-circuits the load across which the tube normally develops its output signal. Therefore, the high frequency response of the amplifier depends to a large extent on the amount of shunt capacitance in the circuit. For good high frequency response the shunt capacitance should be kept as small as possible.

At some frequency above the midband frequencies, the output voltage from the amplifier will drop to 70.7 percent and the output power will again decrease to one-half the midband value. This frequency is called the UPPER HALF-POWER FREQUENCY or upper cut-off frequency and is designated as (f_2) in Figure 19-42. The usable range of frequencies consists of those frequencies between (f_1) and (f_2).

Q24. How would an increase in the value of R_g affect the low frequency response of an RC coupled amplifier?

19-35. Complete Thevenin's Equivalent Circuit

When two amplifier stages are coupled together, the components in the coupling network form part of the load across which the output signal of the first stage is developed (see Figure 19-43A). To accurately represent the amplifier, the equivalent circuit must include all of the resistances and capacitances which appear in the coupling network. This leads to the equivalent circuit in Figure 19-43B.

Because the solution of the complete equivalent circuit is arduous when a single frequency is involved, and becomes drudgery when many frequencies throughout the audio spectrum must be analyzed, it is to ones advantage to develop short-cut methods by which the gain and output voltage can be obtained. One such simplification consists of dividing the audio spectrum into three sections called the high, medium, and low frequency bands. If each band of frequencies is then considered separately, some of the quantities in the complete equivalent circuit can be neglected and a less complex equivalent circuit can be constructed for that particular band of frequencies. For example, at a frequency of 50 kc the reactance of the 0.01 uf coupling capacitor is approximately 318 ohms, a value so insignificant when compared to the 500,000 ohm grid leak resistor that the capacitor can be replaced with a piece of wire as far as the signal is concerned. By utilizing a number of these simplifications, a less complicated equivalent circuit can be developed for each of the three subdivisions of the audio spectrum.

19-36. Midband Equivalent Circuit

For frequencies near the center of the audio spectrum the coupling capacitor is essentially a short-circuit and can, therefore, be eliminated from the equivalent circuit. At these same frequencies the shunt capacitance of 100 pf

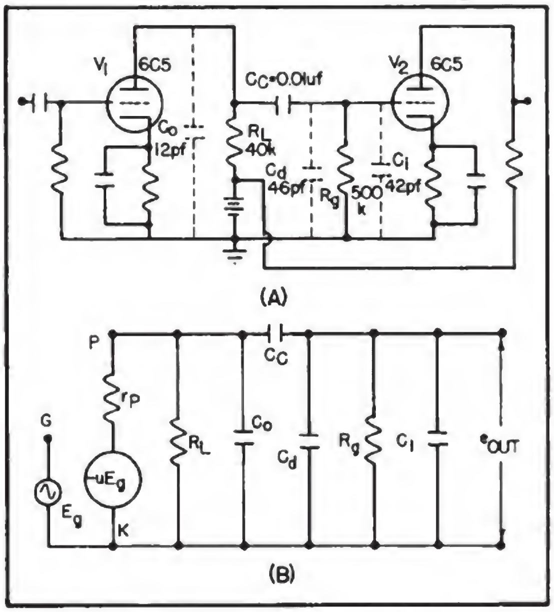

Figure 19-43 - Audio amplifier and equivalent circuit.

formed by the tube elements and circuit wiring has such a high reactance as to appear as an open circuit. In fact, at 400 cycles per second the reactance of the total shunt capacitance is nearly four megohms—100 times the resistance of the plate load resistor. If the impedance of the parallel combination of shunt reactance and plate load resistance is computed it is found to be nearly the same as the value of the plate load resistance taken alone. Therefore, the shunt capacitance can be dispensed within the equivalent circuit.

Since neither the coupling capacitor nor the shunt capacitance is significant at frequencies near the center of the amplifiers range, these quantities can be removed from the equivalent circuit. The quantities remaining from the MIDBAND EQUIVALENT CIRCUIT shown in Figure 19-44A. A further simplification can be made by combining parallel resistances R_L and R_g into one equivalent resistance R_o. The mid-band equivalent circuit then appears as shown in Figure 19-44B. Notice that the generator voltage in the equivalent circuit is expressed as $\mu E_g\angle 180^\circ$ instead of $-\mu E_g$ to more conveniently show the phase reversal between grid and plate signals.

By applying the voltage divider equation from Chapter 7 to the equivalent circuit in Figure 19-44B, the output voltage from the amplifier can be obtained in one step. Since the source voltage is $\mu E_g\angle 180^\circ$, the output voltage (E_o) is:

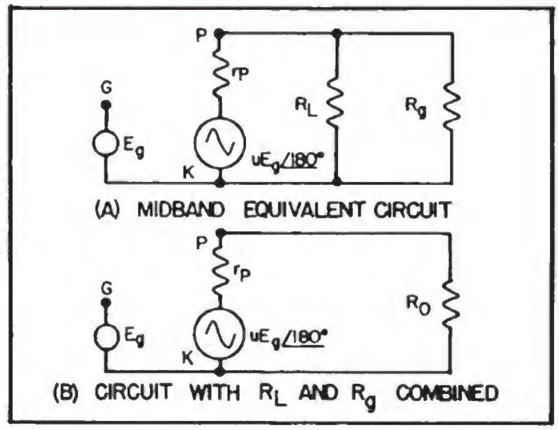

Figure 19-44 - Mid frequency equivalent circuits for a triode amplifier.

$$E_o = \frac{\mu E_g R_o \angle 180^\circ}{r_p + R_o} \qquad (19\text{-}17)$$

where: E_o = RMS output signal from the amplifier
μ = the amplification factor of the tube
r_p = the dynamic plate resistance
R_o = the equivalent resistance of R_L and R_g
E_g = RMS input signal voltage

Another important equation can be derived by manipulation of equation (19-17). Dividing both sides of equation (19-17) by E_g:

$$\frac{E_o}{E_g} = \frac{\dfrac{\mu E_g R_o \angle 180^\circ}{r_p + R_o}}{E_g}$$

and:

$$\frac{E_o}{E_g} = \frac{\mu R_o \angle 180^\circ}{r_p + R_o}$$

Since E_o divided by E_g is the voltage gain of the amplifier:

$$A_v = \frac{\mu R_o \angle 180^\circ}{r_p + R_o} \qquad (19\text{-}18)$$

It should be pointed out that equation (19-18) is nearly identical to equation (19-15), differing only in that equation (19-18) takes the loading effect of the grid leak resistor of the following stage into consideration.

As an example, the midband gain of V_1 in Figure 19-43A is obtained as follows: First,

A24. The low frequency response would be improved, since the increased resistance would cause more of the low frequency signal to develop across the resistor and less to drop across the coupling capacitor.

---

compute the equivalent resistance of R_L and R_g in parallel:

$$R_o = \frac{R_L R_g}{R_L + R_g}$$

$$R_o = \frac{(40\times10^3)(500\times10^3)}{(40\times10^3)+(500\times10^3)}$$

$$R_o = 37,000 \text{ ohms}$$

From the tube manual u and r_p are found to be 20 and 10,000 ohms respectively. Inserting the required quantities into equation (19-18):

$$A_v = \frac{\mu R_o \angle 180^\circ}{r_p + R_o} \qquad (19\text{-}18)$$

$$A_v = \frac{20 \times 37 \times 10^3 \angle 180^\circ}{47 \times 10^3 \angle 0^\circ}$$

$$A_v = 15.7$$

Thus, the midband frequency signals are amplified approximately 15.7 times.

19-37. Low Frequency Equivalent Circuit

As the frequencies applied to the amplifier become lower the reactance of the coupling capacitor rises to an appreciable value, and the midband equivalent circuit and equation (19-18) are no longer valid. The reactance of the shunt capacitance at the low frequencies is higher than at the midband frequencies and again can be disregarded.

The Thevenin's low frequency equivalent circuit is shown in Figure 19-45A. Notice, that the low frequency equivalent is very similar to the midfrequency equivalent with the exception that the coupling capacitor is included between the plate load resistor and the grid leak resistor.

Although the equivalent circuit shown in Figure 19-45A is usable for computing the low frequency gain and output voltage, the solution of the amplifier can be simplified by converting

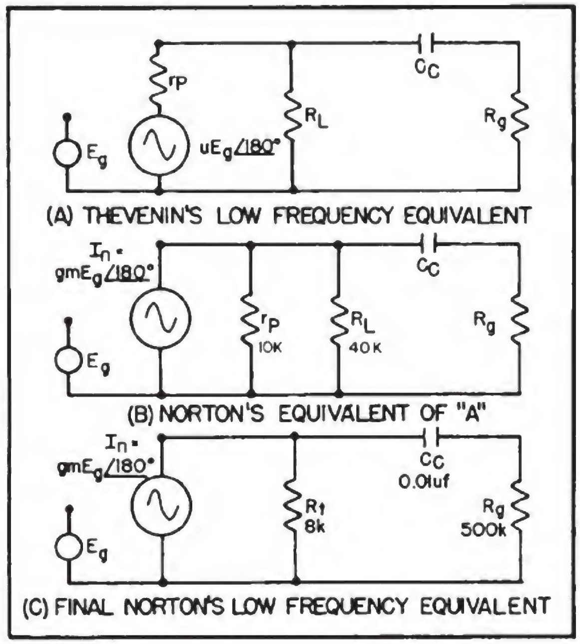

Figure 19-45 - Low frequency equivalent circuits for a triode amplifier.

the Thevenin's constant voltage equivalent circuit into a Norton's constant current equivalent circuit. In section 7-21 it was shown that a relationship exists between Thevenin's and Norton's equivalent circuits such that:

$$E_{th} = I_n Z_{th} \qquad (7\text{-}12)$$

where: E_{th} = the source voltage in Thevenin's equivalent circuit
I_n = the source current in Norton's equivalent circuit
Z_{th} = the series impedance in Thevenin's equivalent circuit

Solving equation (7-12) for I_n:

$$I_n = \frac{E_{th}}{Z_{th}}$$

Substituting the symbols from the vacuum tube equivalent circuit:

$$I_n = \frac{\mu E_g \angle 180^\circ}{r_p}$$

or:

$$I_n = \frac{\mu}{r_p} \times \frac{E_g \angle 180^\circ}{1}$$

Since μ/r_p is equal to gm (equation 19-9) substitution yields:

$$I_n = gm\, E_g \angle 180^\circ \qquad (19\text{-}19)$$

This result (equation 19-19) shows that the source current in Norton's equivalent circuit for a vacuum tube amplifier is equal to the grid signal voltage multiplied by the transconductance of the tube. The angle of 180° indicates that the output signal polarity is opposite to the input signal polarity.

Norton's equivalent circuit is shown in Figure 19-45B. In this equivalent circuit the internal impedance of the generator is placed in parallel with a constant current generator, rather than in series with a constant voltage generator as in Thevenin's equivalent circuit. A further simplification of the equivalent circuit in Figure 19-45B can be made by combining parallel resistances r_p and R_L into a single equivalent resistance R_t. This produces the final low frequency equivalent circuit shown in Figure 19-45C.

Using the Norton's equivalent circuit in Figure 19-45C a formula can be derived for computing the low frequency gain of the amplifier. The derivation of this formula is somewhat lengthy, and for this reason, is not presented at this point. However, the derivation is included at the end of Chapter 20 for those interested.

$$A_{lf} = \frac{gm\, R_t R_g \angle 180^\circ}{R_t + R_g - jX_{cc}} \qquad (19\text{-}20)$$

where: A_{lf} = the low frequency gain.
gm = the transconductance of the tube
R_t = the equivalent resistance of r_p and R_L in parallel
R_g = the resistance of the grid leak resistor of the following stage
X_{cc} = the reactance of the coupling capacitor at the frequency at which the gain is to be computed.

To show the application of equation (19-20) assume that the gain of the first of the two-stage amplifier illustrated in Figure 19-43A is to be computed for a frequency of 50 cycles per second. For convenience the necessary part values from this amplifier have been included in the Norton's equivalent circuit shown in Figure 19-45C.

The first step in finding the gain of the amplifier at 50 cps is to obtain values for those quantities in equation (19-20) which are not given. At 50 cps the reactance of the coupling capacitor is:

$$X_{cc} = \frac{1}{2\pi f C}$$

$$X_{cc} = \frac{1}{6.28 \times 50 \times 0.01 \times 10^{-6}}$$

$$X_{cc} = -j\,318,000 \text{ ohms or } -j\,318\text{ K ohms}$$

Next, the equivalent resistance of r_p and R_L is computed:

$$R_t = \frac{r_p R_L}{r_p + R_L}$$

$$R_t = \frac{(10 \times 10^3)(40 \times 10^3)}{(10 \times 10^3)+(40 \times 10^3)}$$

$$R_t = 8,000 \text{ ohms or } 8 \text{ K ohms}$$

After the transconductance of the 6C5 tube is obtained from the tube manual (2000 micromhos), the required quantities are inserted into equation (19-20):

$$A_{lf} = \frac{gm\, R_t R_g \angle 180^\circ}{R_t + R_g - jX_{cc}} \qquad (19\text{-}20)$$

$$A_{lf} = \frac{2\times10^{-3}\times8\times10^3\times500\times10^3 \angle 180^\circ}{(508\times10^3) + (-j\,318\times10^3)}$$

$$A_{lf} = \frac{8 \times 10^6 \angle 180^\circ}{(508\times10^3) + (-j\,318\times10^3)}$$

Converting the denominator to polar form:

$$\theta = \arctan \frac{-j\,318 \times 10^3}{508 \times 10^3}$$

$$\theta = -32^\circ$$

The magnitude (m) of the denominator is:

$$m = \frac{-jX_{cc}}{\sin\theta}$$

$$m = \frac{318 \times 10^3}{0.53}$$

$$m = 6 \times 10^5$$

or:

$$A_{lf} = \frac{8 \times 10^6 \angle 180^\circ}{6 \times 10^5 \angle -32^\circ}$$

$$A_{lf} = 13.3 \angle 212^\circ$$

This computation shows that the gain of the amplifier at a frequency of 50 cps is 13.3. This is only about 85 percent as much gain as a signal in the center of the band receives. Moreover, the 50 cps signal is shifted 212° minus 180°, or, 32° in addition to the normal phase inversion provided by the action of the tube. This additional phase shift is caused by the reactance of the coupling capacitor.

Q25. What change could be made in the coupling network of an RC coupled amplifier to produce less phase shift in signals at the low frequency end of the spectrum?

19-38. High Frequency Equivalent Circuit

At the high frequency end of the audio spectrum the reactance of the coupling capacitor is very low and, as was the case with the midband conditions, can be neglected. Since the reactance of the interelectrode and wiring capacitance is likewise inversely proportional to frequency, it too decreases as the frequency of the signal is increased. Owing to the fact that the interelectrode and wiring capacitance is in shunt (parallel) with the plate and grid resistors of the amplifier, it tends to short-circuit these resistors at the higher audio frequencies lowering the high frequency gain. This capacitance must, therefore, be included in the high frequency equivalent circuit.

The high frequency Thevenin's equivalent circuit is illustrated in Figure 19-46A. Notice, that the coupling capacitor is not included, and that C_o, C_i, and C_d have been combined into a single shunt capacitance C_s. In the amplifier of Figure 19-43, C_s is 100 picofarads.

A more convenient equivalent circuit can be obtained by converting the Thevenin's equivalent

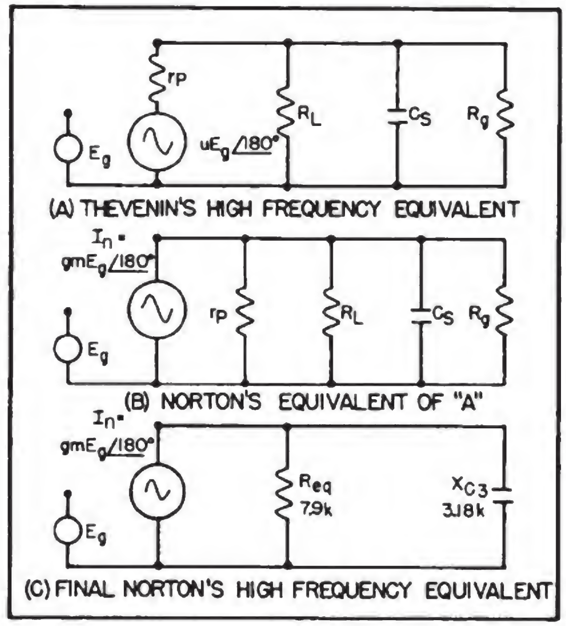

Figure 19-46 - High frequency equivalent circuits for a triode amplifier.

circuit in Figure 19-46A to the Norton's equivalent circuit shown in part B of the diagram. By combining parallel resistances r_p, R_L, and R_g into a single equivalent resistance R_{eq}, the simple two branch circuit in Figure 19-46C results. This circuit is called Norton's high frequency equivalent circuit.

Proper manipulation of the quantities in the high frequency equivalent circuit leads to equation (19-21) which is used to compute the high frequency gain of an RC coupled amplifier. (The derivation of this equation is included at the end of Chapter 20.)

$$A_{hf} = \frac{(gm\, R_{eq} \angle 180^\circ)(X_{cs} \angle -90^\circ)}{R_{eq} - jX_{cs}} \qquad (19\text{-}21)$$

where: A_{hf} = the high frequency gain
R_{eq} = the equivalent resistance of r_p, R_L and R_g in parallel
X_{cs} = the reactance of the total shunt capacitance (C_s) at the frequency for which the gain is desired

To illustrate the application of equation (19-21) the gain of the amplifier in Figure 19-43 will be computed for a frequency of 500 kilocycles. The high frequency equivalent circuit for this amplifier is shown in Figure 19-46C.

In order to use equation (19-21) values must be obtained for R_{eq} and the reactance of C_s.

These quantities are:

$$R_{eq} = \frac{r_p R_L R_g}{r_p R_L + r_p R_g + R_L R_g}$$

$$R_{eq} = \frac{(10\times10^3)(40\times10^3)(500\times10^3)}{(400\times10^6)+(5000\times10^6)+(20,000\times10^6)}$$

$$R_{eq} = \frac{20,000 \times 10^{10}}{25,400 \times 10^6}$$

$$R_{eq} = 7.9 \text{ K ohms}$$

and:

$$X_{cs} = \frac{1}{2\pi f C_s}$$

$$X_{cs} = \frac{1}{6.28 \times 500 \times 10^3 \times 100 \times 10^{-12}}$$

$$X_{cs} = \frac{1}{31.4 \times 10^{-5}}$$

$$X_{cs} = 3.18 \text{ K ohms}$$

Inserting the required values into equation (19-21), the gain of the amplifier is found to be:

$$A_{hf} = \frac{(g_m R_{eq} \angle 180^\circ)(X_{cs} \angle -90^\circ)}{R_{eq} - jX_{cs}} \qquad (19\text{-}21)$$

$$A_{hf} = \frac{(2\times10^{-3}\times7.9\times10^3 \angle 180^\circ)(3.18\times10^3 \angle -90^\circ)}{(7.9\times10^3)-(j3.18\times10^3)}$$

Converting the denominator to polar form:

$$\theta = \arctan \frac{-j3.18\times10^3}{7.9\times10^3}$$

$$\theta = -21.9^\circ$$

The magnitude (m) of the denominator is:

$$m = \frac{-jX_{cs}}{\sin\theta}$$

$$m = \frac{3.18\times10^3}{0.373}$$

$$m = 8.54 \times 10^3$$

Completing the equation:

$$A_{hf} = \frac{50.3 \times 10^3 \angle 90^\circ}{8.54 \times 10^3 \angle -21.9^\circ}$$

$$A_{hf} = 5.9 \angle 111.9^\circ$$

Thus, the gain of the amplifier at 500 kilocycles is 5.9, approximately 37.5 percent of the gain obtained for a midband frequency. The reactance of the shunt capacitance causes the output signal to lag 68.1° behind the normal 180° polarity inversion.

Q26. Other factors equal, which tube would give better high frequency response, a high mu triode or a low mu triode?

19-39. A Typical Response Curve

Once the equations are available for computing the high, middle, and low frequency gains, the response curve for a given amplifier stage can be sketched on a sheet of graph paper. Since the ear is logarithmic in nature, most response curves are plotted on logarithmic graph paper.

The data required to construct a response curve for the amplifier in Figure 19-43A has been computed using equations (19-18), (19-20), and (19-21). This data is shown in Table 19-1 for a series of frequencies between 10 cycles per second and 5 megacycles per second. Notice, that the gain is maximum and the phase shift minimum for those frequencies near the center of the band. For frequencies far from the center of the band, the gain is low and the amount of phase shift is large.

Freq. (cps)	X_{cs} in ohms	X_{cc} in ohms	Gain	θ
10	159 M	1.59 M	4.8	252°
50	31.8 M	318 k	13.3	212°
100	15.9 M	159 k	15.1	197°
500	3.18 M	31.8 k	15.8	184°
1 kc	1.59 M	15.9 k	16.0	180°
5 kc	318 k	3.2 k	16.0	180°
10 kc	159 k	1.6 k	16.0	180°
50 kc	31.8 k	318	15.5	166°
100 kc	15.9 k	159	14.3	153°
500 kc	3.18 k	31.8	5.9	112°
1 Mc	1.6 k	15.9	3.6	101°
5 Mc	318	3.18	0.64	92°

Table 19-1 - Circuit gain as a function of frequency. Values based on the circuit illustrated in Figure 19-43.

A25. The value of either the coupling capacitor or grid leak resistor could be increased.

A26. Since the input capacitance increases with an increase in stage gain (Miller effect) the low mu triode would produce high frequency response, other factors equal.

The response curve for the amplifier is shown in Figure 19-47. The half-power points f_1 and f_2 are marked on the curve to define the operating limits of the amplifier. Since f_1 occurs at a frequency of 30 cycles per second and f_2 occurs at a frequency of 200 kilocycles per second, the amplifier has a useable range or BANDWIDTH of 199,970 cycles per second (f_2 - f_1).

Although the amplifier appears to have more than the required high frequency response for audio applications, this is a desirable condition in many cases. Quite often waveforms which occur at an audio rate contain frequency components considerably higher than 20,000 cycles per second. To accurately reproduce these waveforms the amplifier must have good high frequency response.

Figure 19-47 also contains a curve showing the phase of the output signal voltage as a function of frequency. For signals at frequencies near the center of the band, the phase shift is zero and only the 180 degree phase inversion occurs. At frequencies above the midband range the output voltage lags behind 180 degrees, while at frequencies below the midband range the output voltage leads.

DISTORTION

The ability of an amplifier to accurately reproduce the waveform of the input signal is called the FIDELITY of the amplifier. To have good fidelity the output signal waveform should be identical to the input signal waveform in every respect except amplitude. If a change other than an increase in amplitude does occur during the process of amplification the waveform is said to be DISTORTED. Normally, distortion in an amplifier is undesirable. However, to achieve the special waveforms required in certain radar, television, and test circuitry, distortion is deliberately introduced by an amplifier or an associated circuit. The three general types of distortion are AMPLITUDE DISTORTION, FREQUENCY DISTORTION, and PHASE DISTORTION.

19-40. Amplitude Distortion

Amplitude or non-linear distortion occurs whenever the signal operates over a non-linear section of an amplifiers characteristic curve. Amplitude distortion can be caused by the use of improper bias or too large an input signal. Severe amplitude distortion is introduced into the signal if peak clipping occurs as a result of driving the tube into cut-off, or to the point of grid current flow. Distortion caused by grid

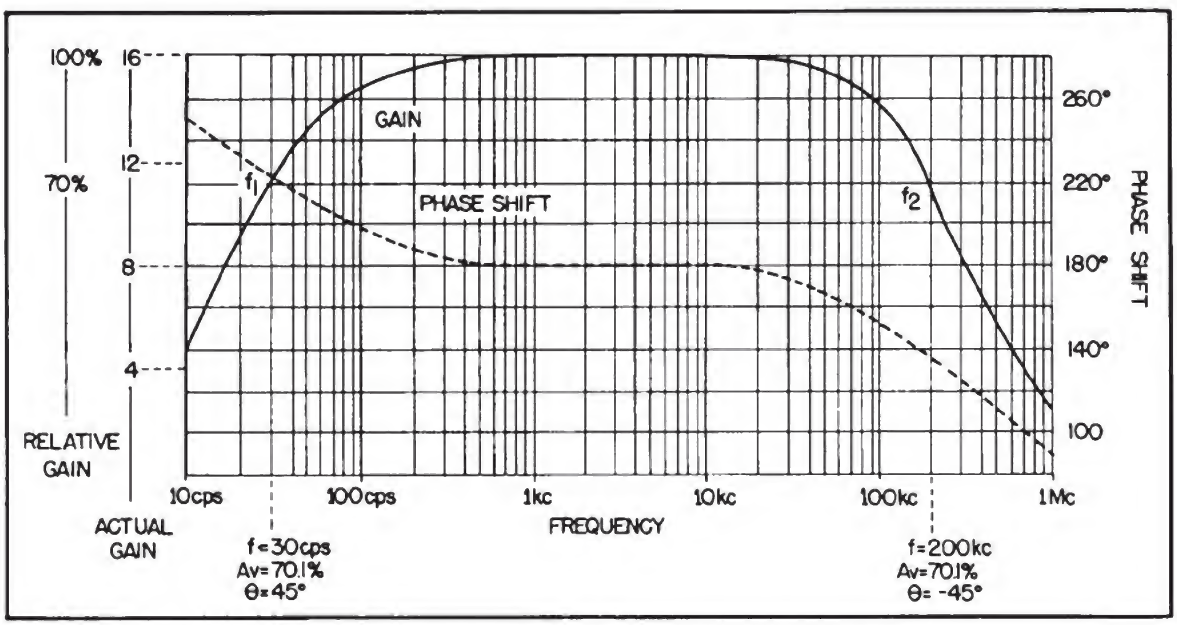

Figure 19-47 - Response curve for amplifier in Figure 19-43.

current results when the grid current causes a portion of the applied signal to drop inside the source as a result of the high internal impedance of the source.

19-41. Frequency Distortion

Frequency distortion is present when some frequency components of a complex signal are amplified more than others. For the most part, frequency distortion is introduced into the signal because of the variable reactance of C_c and C_s as discussed previously in the section on frequency response. Frequency distortion can be kept to a minimum by insuring that the bandwidth of the amplifier is wide enough to include all significant frequency components of the signal.

19-42. Phase Distortion

Phase distortion exists when the phase relationships between the frequency components of the output signal are not the same as in the input signal. The phase shift curve discussed in section 19-39 pointed up the fact that the amplifier becomes highly reactive at frequencies far above and below the midband frequencies. At these frequencies the phase shift becomes nearly 90 degrees. Thus, if high, medium and low frequency signals are simultaneously applied to the input of an amplifier the midrange frequency will be amplified with little or no phase shift, the high frequency will be caused to lag its former phase, and the low frequency signal will be caused to lead with respect to its original phase. Since the three signals have been shifted in time, relative to each other, they no longer produce the same complex waveform when added together in the output of the amplifier.

In the chapters to follow, the vacuum tube amplifier theory and methods of analysis developed in this chapter will be enlarged upon and extended to aid in the understanding of other electronic circuits. For convenience, a table of symbols commonly used for vacuum tube circuits follows. This table is also included in Volume VIII.

SYMBOLS USED IN VACUUM TUBE CIRCUITS

E_b. . . Plate voltage (dc)
I_b. . . . Plate current (dc)
E_{c1}. . Control grid voltage
E_{c2}. . Screen grid voltage
E_{bo}. . Quiescent plate voltage
I_{bo}. . . Quiescent plate current
E_{bb}. . Plate supply voltage
E_{cc}. . Control grid supply voltage
E_p. . . RMS value of plate voltage
I_p. . . . RMS value of plate current
E_g. . . RMS value of grid volts
I_{g2}. . . RMS value of screen grid current
e_g. . . Instantaneous value of grid volts (ac)
i_p. . . . Instantaneous plate current (ac)
i_g. . . . Instantaneous grid current (ac)
e_b. . . Instantaneous total plate volts (ac and dc)
i_b. . . . Instantaneous total plate current (ac and dc)
e_{c1}. . Instantaneous total control grid volts (ac and dc)
e_{c2}. . Instantaneous total screen grid volts (ac and dc)
E_f. . . Filament, or heater, terminal volts
I_f. . . . Filament, or heater, current
I_s. . . . Total electron emission
r_p. . . Plate resistance (ac)
gm. . . Grid-plate transconductance (mutual conductance)
μ. . . . Amplification factor
R_b. . . Plate resistance (dc)
C_{gp}. . Grid-to-plate capacitance
C_{gk}. . Grid-to-cathode capacitance
C_{pk}. . Plate-to-cathode capacitance
A_v. . . Voltage gain
A_{hf}. . High frequency gain
A_{lf}. . . Low frequency gain
C_c. . . Coupling capacitor
C_d. . . Distributed capacitance
C_i. . . Input capacitance
C_k. . . Cathode bypass capacitor
C_o. . . Output capacitance
C_s. . . Shunt capacitance (C_d+C_i+C_o)
R_g. . . Grid leak resistor
R_k. . . Cathode resistor
R_L Plate load resistor

EXERCISE 19

1. How does the construction of a triode differ from the construction of a diode?
2. What is the function of the grid in a triode?
3. What determines the direction and strength of the electrostatic fields within the tube?
4. Why does the grid voltage of a triode exercise more control over plate current than does the plate voltage?
5. If heat is generated at the plate of a tube faster than the tube can dissipate the heat, which tube rating is being exceeded?
6. What happens to the electrons which accidentally collide with the grid wires during normal operation of a triode vacuum tube?
7. What happens to the amount of plate current flow in a triode vacuum tube if the grid is made less negative?
8. What happens to the amount of plate current flow in a triode if the plate is made less positive?
9. Describe the changes that occur in the electrostatic field within the tube as the grid voltage is made more negative.
10. Explain the meaning of the term "cut-off" as applied to the triode vacuum tube.
11. Explain the difference between a static characteristic curve and a dynamic characteristic curve.
12. When plotting a plate family of characteristic curves which quantity is used as the dependent variable?
13. Why is the plate family of curves the only family normally published in the tube manual?
14. Using the plate family of curves for a 6J5 (Figure 19-11) determine the values of plate current that would result if the plate is maintained at 150 volts and the grid voltage is adjusted from zero to the cut-off value in 2 volt steps.
15. What is the name and purpose of the resistor connected between the plate of an amplifier tube and the positive terminal of E_{bb}?
16. Explain why the voltage change which occurs at the plate of a triode amplifier is always in a direction opposite to the voltage change occurring in the grid circuit.
17. Why is the dc load line for the triode amplifier straight rather than curved?
18. Find the value of the plate load resistor if a tube operating from a supply voltage of 300 volts has a plate voltage of 200 volts and a plate current of 5 milliamperes.
19. What would be the Y-axis intercept of a dc load line constructed for an amplifier having a supply voltage of 300 volts, a plate load resistor of 15,000 ohms, and a grid voltage of 4 volts?
20. Construct a dc load line for an amplifier using a supply voltage of 300 volts, a plate load resistor of 50,000 ohms, and a 6J5 tube, then determine the X-axis and Y-axis intercepts. (A family of curves can be sketched by placing a thin piece of paper over one of the families in the text and then tracing the desired curves.)
21. Explain the meaning of "quiescent operation".
22. Using the load line from question 20, determine the quiescent plate voltage (E_{bo}) and the quiescent plate current (I_{bo}) for a bias of -2 volts.
23. Assuming an input signal of one volt peak, and a bias voltage of -2 volts determine: the maximum and minimum values of plate voltage and plate current, the RMS output signal voltage, and the voltage gain of the amplifier (use the load line from question 20).
24. What conclusion could be drawn concerning the plate load resistor of an amplifier if the load line for the amplifier is: (a) nearly vertical? (b) nearly horizontal?
25. How would an increase in supply voltage affect the slope of the dc load line?
26. Why is the static transfer characteristic different from the dynamic transfer characteristic even though both curves are "E_c - I_b" curves?
27. How would the dynamic transfer characteristic for an amplifier appear if the plate supply becomes very low?
28. Compare class A, AB, B, and C operation as to the following: (a) distortion (b) efficiency (c) input signal amplitude requirements.
29. How much output power would be obtained from an amplifier if E_b = 250 volts, I_b = 20 milliamperes, and the efficiency is 40%?
30. If a dc milliammeter is connected in series with the plate of an ideal class A amplifier and the amplitude of the input signal is then increased from zero to its normal maximum value, what indication would be observed on the meter?
31. What indication would be observed on the meter in question 30 if the amplifier was operating class B?
32. In class AB_2 operation what does the subscript "2" indicate?
33. What is "bias"?
34. Why is bias used?
35. Explain how cathode bias is developed.
36. What would be the value of plate current in a class A amplifier which obtains its 3 volts of bias from a 600 ohm R_k?

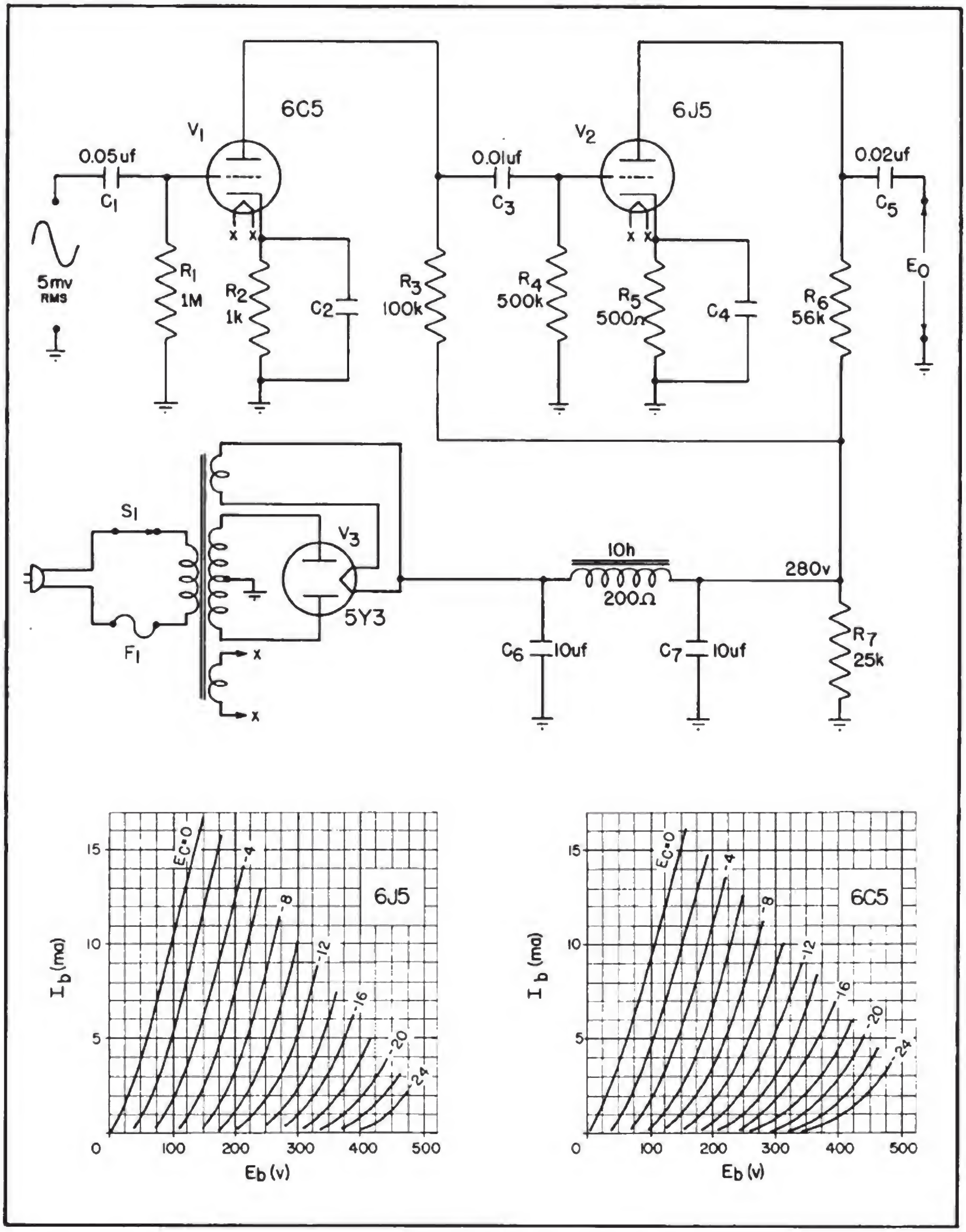

Figure 19-48 - Complete amplifier schematic.

EXERCISE 19 (continued)

37. Why would it be impractical to use a cathode resistor to supply the operating bias for a class C amplifier?
38. Why is a large value of capacitance sometimes connected in parallel with the cathode resistor of an amplifier?
39. What is the lowest frequency at which a 30 microfarad cathode bypass capacitor would be suitable in the amplifier of question 36?
40. Why is a cathode bias line used?
41. Is the cathode bias line a straight line?
42. What is a cascade amplifier?
43. What is the purpose of a coupling capacitor?
44. Describe the charge and discharge paths for the coupling capacitor in a two-stage amplifier.
45. Explain how the signal is transferred from the plate of one tube to the grid of the next in an RC coupled amplifier.
46. What should the time constant of the coupling capacitor be as compared to the period of the signal being amplified?
47. Why is an ac load line necessary?
48. What is the amplification factor of a tube?
49. What is the dynamic plate resistance of a tube?
50. What is the transconductance of a tube?
51. A technician observes that a 30 volt increase in the plate voltage applied to a certain triode causes a 1.5 milliampere increase in plate current, which in turn can be nullified by a 1.0 volt increase in the negative grid bias. Find the three tube parameters for this triode.
52. Why is an equivalent circuit useful?
53. Compute the midband gain of a single stage amplifier in which u = 20, r_p = 10,000 ohms and R_L = 40,000 ohms.
54. What is the Miller effect?
55. What factors cause the high frequency gain of an RC coupled amplifier to be less than the midband gain?
56. What factors cause the low frequency gain of an RC coupled amplifier to be less than the midband gain?

Answer the following questions using Figure 19-48.

57. What type of power supply is used?
58. What type of bias is used on V_2?
59. What is the purpose of R_3?
60. What is the purpose of R_4?
61. Construct a load line and cathode bias line for V_1 and V_2 and determine the following dc voltages and currents:

$V_1 I_b$ = ?	E_{R4} = ?
$V_1 E_b$ = ?	E_{R5} = ?
V_1 Bias = ?	E_{R6} = ?
$V_2 I_b$ = ?	E_{R7} = ?
$V_2 E_b$ = ?	E_{C2} = ?
V_2 Bias = ?	E_{C3} = ?
E_{R1} = ?	E_{C4} = ?
E_{R2} = ?	E_{C6} = ?
E_{R3} = ?	E_{C7} = ?

62. What is the total current drawn from the power supply?
63. What is the dc voltage drop across the power supply filter choke?
64. Compute the amplitude and phase of the output signal for a frequency of one kilocycle. Use the input signal shown on Figure 19-48.
65. What is the total midband gain of this amplifier?
66. What is the gain of V_1 at a frequency of 50 cycles per second?
67. What should the size of C_2 be if f_1 is 50 cycles per second?
68. What is the gain of V_1 at a frequency of 100 kilocycles? (Assume a shunt capacitance of 60 picofarads.)
69. What would happen to the low frequency response of the amplifier if R_4 was reduced in value?
70. What would happen to the high frequency response if R_3 was reduced to 20,000 ohms?

CHAPTER 20

TETRODE AND PENTODE AMPLIFIERS

Although triode vacuum tubes find wide employment in amplifiers, oscillators, and numerous other applications, the triode has certain unavoidable disadvantages. One of the more prominent disadvantages of the triode tube is the relatively large capacitances which exist between the elements.

Capacitance exists between any two metal surfaces separated by a dielectric. The amount of capacitance depends on the area of the metal surfaces, the distance between them, and the type of dielectric. In a triode tube the three metal electrodes, in conjunction with the vacuum which acts as a dielectric, form three INTERELECTRODE CAPACITANCES. These capacitances are: the grid-to-cathode capacitance (C_{gk}), the grid-to-plate capacitance (C_{gp}), and the plate-to-cathode capacitance (C_{pk}).

At low and medium frequencies the interelectrode capacitance, as well as the distributed capacitances due to circuit wiring, have only a slight shunting effect because the reactance at these frequencies is high compared with the impedance of other circuit components.

At high frequencies the interelectrode and distributed capacitances cause appreciable shunting effect and loss of gain due to the reduced reactance at these frequencies.

An additional undesirable effect occurs as a result of the grid-to-plate capacitance of a triode. When the tube is used as an amplifier, energy from the plate circuit is coupled back through the grid-to-plate capacitance to the grid circuit. If the energy coupled back opposes the original grid signal the gain of the amplifier will be reduced. If the energy is coupled back in phase with the grid signal, the amplifier is likely to break into undesirable oscillation.

In an effort to surmount the difficulties encountered at high frequencies, experiments were performed in which additional grids were added to the tube. From these experiments emerged the four element TETRODE containing two grids and the five element PENTODE containing three grids.

TETRODES

20-1. Tetrode Construction

The relatively large values of interelectrode capacitances of the triode, particularly the grid-to-plate capacitance, impose a serious limitation on the tube as an amplifier at high frequencies. To reduce the grid-to-plate capacitance, a grid called a SCREEN GRID (G_2) is inserted between the control grid and plate of the tube as shown in Figure 20-1. Structurally the screen grid is somewhat similar in appearance to the control grid.

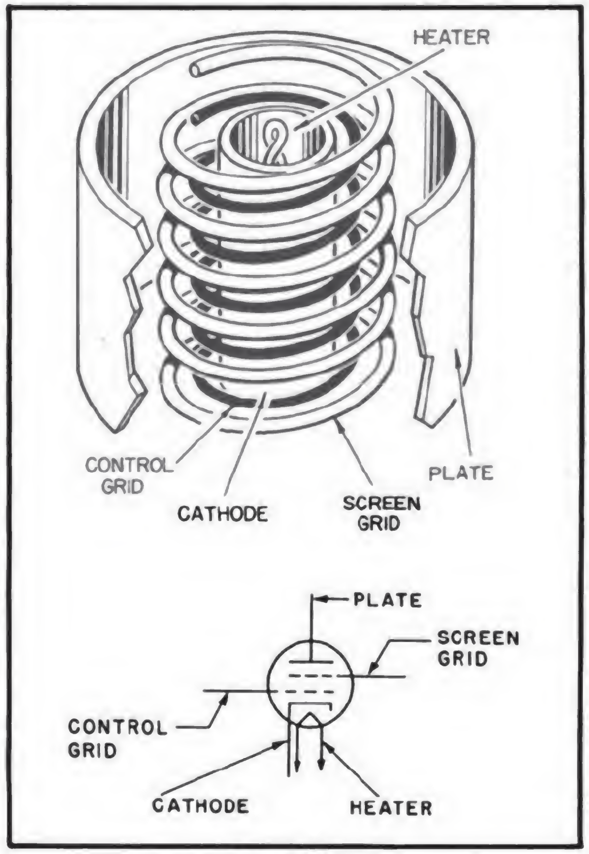

Figure 20-1 - Construction and schematic symbol for a tetrode tube.

20-2. Function of the Screen Grid

The primary purpose of the screen grid is to act as an electrostatic shield between the control grid and the plate. By placing the screen grid between the control grid and plate, the

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original grid to plate capacitance is divided into two series capacitances consisting of the control grid to screen capacitance and the screen grid to plate capacitance as shown in Figure 20-2A. This reduces the control grid-to-plate capacitance by a considerable amount.

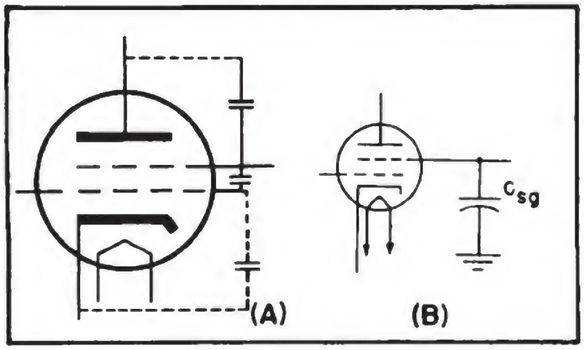

Figure 20-2 - Shielding effect of screen grid.

To increase the effectiveness of the shielding between control grid and plate, the screen grid should be connected to the cathode or to chassis ground. This cannot be a direct connection however, since the screen grid must be at a positive dc potential for proper operation of the tube. This indicates that the external screen-to-cathode circuit must appear as a short circuit to ac, but as an open circuit to dc. These two conditions are met by placing a capacitor between screen grid and ground as in Figure 20-2B. This capacitor is called a SCREEN BYPASS CAPACITOR (C_{sg}), and must have a capacitance large enough to present a very low reactance to the operating frequency of the circuit.

Normally the screen grid is operated at a positive potential with respect to the cathode. As a result of this, most of the electrostatic lines of force within the tube are set-up between the screen and control grid and screen and space charge. Only a small number of the lines of force originating on the plate are able to extend through the screen and control grids to the electrons in the space charge.

Since few lines of force exist between the plate and space charge, changes in plate voltage have little effect on the number of electrons in transit between the cathode and screen grid areas of the tube. This serves to make the number of electrons striking the plate (and therefore the plate current) nearly independent of plate voltage. Due to the shielding effect of the screen, the plate becomes merely a collector of electrons, and can be likened to a photographic plate which collects light, but exercises no control over the amount of light it receives.

Like any other positive element in a vacuum tube the screen draws a certain amount of current. This current is called SCREEN CURRENT (I_{c2}). Since most of the electrons traveling toward the plate pass through the openings in the screen grid and strike the plate, the screen current is normally much less than the plate current.

Because of the geometry of the tube, the positive voltage applied to the screen grid will have a greater influence on the plate current than a comparable value of positive voltage applied to the plate.

Q1. When a positive voltage is applied to the screen grid, what happens to the cathode current? Explain.

Q2. Which element in the tetrode would have the greatest control of cathode current?

20-3. E_b-I_b Characteristic Curves

The conventional method used to analyze the operation of an electron tube is to utilize its characteristic curves. Figure 20-3 shows a tetrode, the applied voltages, and the resulting characteristic curves. To plot the characteristic curves, the control grid voltage will be held at a constant -3 volts and the screen grid will be held at a positive potential of 100 volts. The plate voltage will then be increased from zero volts to some maximum positive value. Note that all of the voltages and currents for the tube are labeled.

The tube chosen for this discussion is the UY-224 tetrode. The illustration is based on this tube because its characteristic curve well illustrates the disadvantages inherent in all tetrodes. More modern tetrodes have minimized these disadvantages. Specifically, the characteristic negative slope of the tetrode, indicated in Figure 20-3, between points X and Y, is more pronounced in this tube. The area of the negative slope is of primary importance in the study of tetrodes.

Let it be assumed that the circuit is energized, plate voltage is zero, screen voltage is a positive 100 volts, and the control grid voltage is -3 volts. The electrons emitted from the cathode will be attracted toward the positive screen grid. They will pass through the control grid, being slightly retarded by the negative potential applied to the control grid. Since the screen grid is an open mesh, most of the electrons will pass through it. However, as there is no potential applied to the plate, they will return to the screen grid and produce a considerable amount of screen grid current.

If the control grid and screen grid potentials are held constant, and a small positive voltage is applied to the plate, some of the electrons passing through the screen grid mesh will be

attracted toward the plate causing a plate current flow. The plate and screen current values

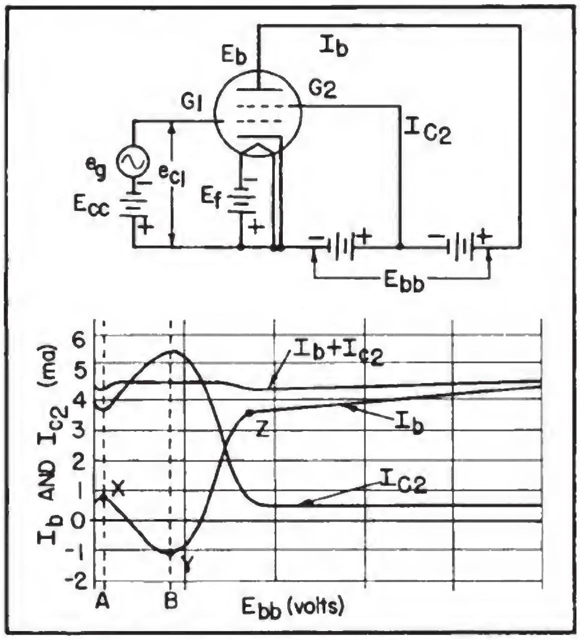

Figure 20-3 - Plate characteristics of a tetrode.

existing with the small plate voltage are shown in Figure 20-3. With a small value of plate voltage applied, the screen current is much higher than the plate current. There are two reasons for this condition: the positive voltage applied to the screen grid is much higher than that applied to the plate, and the screen grid is physically closer to the cathode.

If the plate voltage is increased to point B, a corresponding decrease in plate current occurs. A decrease in plate current being caused by an increase in plate voltage is contrary to conventional tube theory. The reason for this departure from the expected conditions is due to the emission of secondary electrons from the plate. Secondary emission is produced when a material is bombarded by electrons the velocity of which is sufficiently high to dislodge electrons from the material being bombarded. When the plate voltage is increased to point B, electrons emitted from the cathode acquire velocities high enough to cause secondary emission when striking the plate. Since the secondary electrons produced exist in the area between the plate and the screen grid, they will be attracted to the nearest and highest positive potential. The closest element with a high positive potential is the screen grid. These additional free electrons attracted toward the screen grid will cause an increase in the screen grid current. Since the secondary electrons are attracted toward the screen grid, they will not be available to form part of the plate current. The plate current at point B will decrease. The increase in screen current, and corresponding decrease in plate current, is illustrated in Figure 20-3.

An increase in plate voltage accompanied by a decrease in plate current introduces a new term. Ohm's law states that the current is directly proportional to the voltage and inversely proportional to the resistance. When the resistance is held constant, and an increase in voltage causes a decrease in current, the resistance is said to be negative. If an increase in voltage causes an increase in current, the resistance is said to be positive. The decreasing plate current is shown as the negatively sloping line, X-Y, in Figure 20-3. The area from point X to Y is known as the area of negative resistance, or the DYNATRON REGION. The dynatron region will exist until the plate voltage approaches the value of the screen voltage.

As soon as the plate voltage is made greater than the screen voltage, plate current will increase and screen current will decrease. The plate voltage is now sufficiently positive to attract its own secondary electrons plus the primary electrons emitted from the cathode. An additional increase in the value of the plate voltage will cause an increase in plate current. The plate current will continue to increase until it reaches point Z. At this point, plate current does not appreciably increase with an increase in plate voltage. This is due to the positive potential on the screen grid. The plate is only able to attract those electrons that were initially attracted by the screen grid. A change in the screen grid voltage has a greater effect on the cathode emitted electrons than an equal change in plate voltage. The screen grid exercises a greater control over the plate current, in comparison to the plate voltage, because the screen grid is physically closer to the cathode. The normal operating point of the tetrode is to the right of point Z. The bend in the plate current curve near point Z is known as the "KNEE" of the curve.

Modern tetrodes are designed to minimize the effects of the dynatron region. An improved tetrode, such as type 24A, renders a plate family of curves with a greatly reduced region of negative slope. The plate family of curves for this type of tube is illustrated in Figure 20-4. These curves indicate that a greater operating range is possible with the 24A tetrode as compared to the UY-224 tetrode.

Q3. Why can the negative slope of the tetrode E_b-I_b curve be called negative resistance?

A1. The cathode current increases by an amount equal in magnitude to the combined values of plate and screen current.

A2. The control grid will have the greatest control of cathode current because it is the element nearest the cathode.

A3. This area of the curve can be called negative resistance because an increase in plate voltage causes a decrease in plate current.

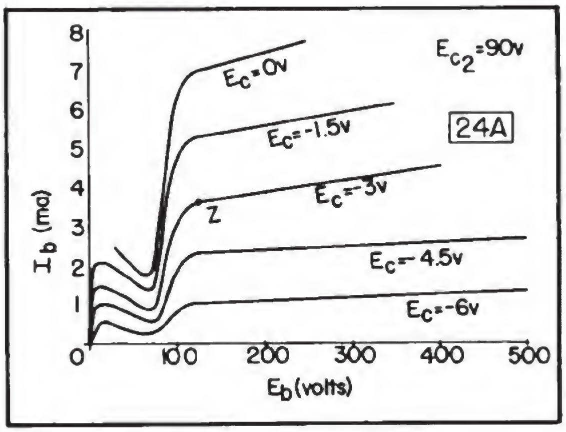

Figure 20-4 - Plate characteristics of improved tetrode.

20-4. Voltage Requirements

Typical value of voltage applied to the elements of a tetrode are: 90 volts applied to the screen grid, 250 volts applied to the plate, and -3 volts applied to the control grid.

It is convenient to supply dc voltages to the tetrode from a common power supply. Since the screen grid voltage requirements are usually much lower than the required plate voltage, a dropping resistor is connected between the voltage source and the screen grid. This connection is shown in Figure 20-5. When screen grid current begins to flow, a voltage will be dropped across the SCREEN DROPPING RESISTOR (R_{sg}). The supply voltage will be distributed across the dropping resistor and from screen grid to ground. The voltage between the screen grid and cathode is the screen grid voltage. Since the screen voltage is critical to the operation of the tetrode, the value of the screen dropping resistor must be accurately computed. The formula that is used to compute the value of the screen dropping resistor is as follows:

$$R_{sg} = \frac{E_{bb} - E_{c2}}{I_{c2}} \qquad (20\text{-}1)$$

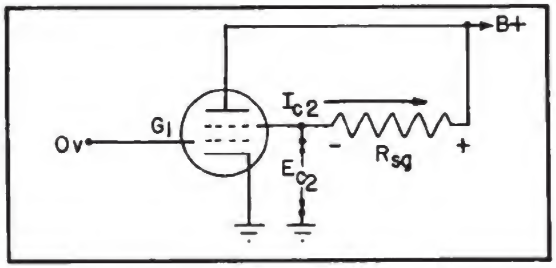

Figure 20-5 - Connection of screen dropping resistor.

where: R_{sg} = resistance of screen resistor in ohms
E_{bb} = supply voltage
E_{c2} = desired screen voltage
I_{c2} = screen current in amperes

The numerator, $E_{bb}-E_{c2}$, is the voltage to be dropped across the screen resistor, and I_{c2} is the current through the screen resistor. If the applied voltage is 275 volts, the screen grid current is 1.7 ma; and the desired screen voltage is 90 volts; the value of the screen dropping resistor may be computed:

$$R_{sg} = \frac{E_{bb} - E_{c2}}{I_{c2}} \qquad (20\text{-}1)$$

substituting values:

$$R_{sg} = \frac{275 - 90 \text{ volts}}{1.7 \times 10^{-3} \text{ amperes}}$$

$$R_{sg} = 109\text{K ohms}$$

Q4. What would happen if the screen dropping resistor were to open while the tetrode is conducting?

TETRODE TUBE CONSTANTS

20-5. AC Plate Resistance

The ac plate resistance of the tetrode is computed in exactly the same manner as the ac plate resistance of the triode. The formula used is:

$$r_p = \left.\frac{\Delta E_b}{\Delta I_b}\right| \Delta E_c = 0 \qquad (19\text{-}6)$$

From the curve in Figure 20-6, it is seen that a change in E_b of 150 volts causes a change in I_b of 0.4 ma. Solving for r_p:

$$r_p = \frac{150\text{V}}{0.4 \text{ ma}} = 375\text{K ohms}$$

Note that the value of the ac plate resistance for a tetrode is considerably higher than that of a triode.

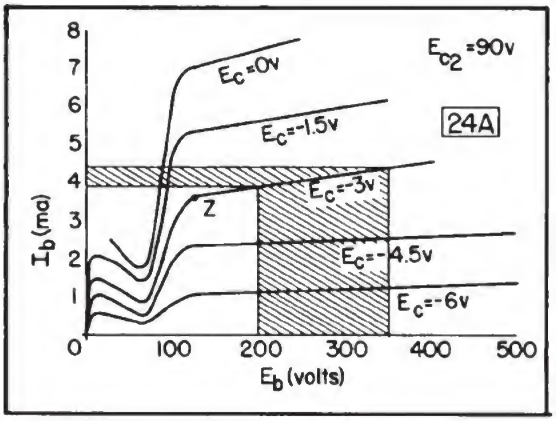

Figure 20-6 - Computing r_p.

Q5. What would be the relative value of the ac plate resistance if the -6 volt curve were used instead of the -3 volt curve?

20-6. Amplification Factor

Values for the amplification factor of tetrodes are difficult to determine from the plate characteristic curves because the horizontal plate current lines do not intersect the flat portions of two adjacent plate characteristic curves. The amplification factor for the tetrode is very high because there is a large change in plate voltage for a very small change in grid voltage. Triodes possess amplification factors in the range of from five to one hundred. Tetrodes having amplification factors of six-hundred are not uncommon. If the change in plate voltage for a given change in grid voltage is known, the value of the amplification factor may be determined by using the following formula:

$$\mu = \frac{\Delta E_b}{\Delta E_c} \Big|\, \Delta I_b = 0 \qquad (19\text{-}5)$$

20-7. Transconductance

A mathematical statement of transconductance is as follows:

$$gm = \frac{\Delta I_b}{\Delta E_c} \Big|\, \Delta E_b = 0 \qquad (19\text{-}7)$$

Using equation (19-7), and the curve shown in Figure 20-7, values for the transconductance of tetrodes may be determined. From the curve, it can be seen that a change of 1.5 volts on the grid corresponds to a change in plate current of 1.8 ma. Substituting these values into the formula:

$$gm = \frac{1.8 \text{ ma}}{1.5\text{V}} = 1200 \text{ micromhos}$$

The figure of 1200 micromhos is an average value of transconductance for lower power tetrodes. High power tetrodes may have transconductance values of 5,000 micromhos.

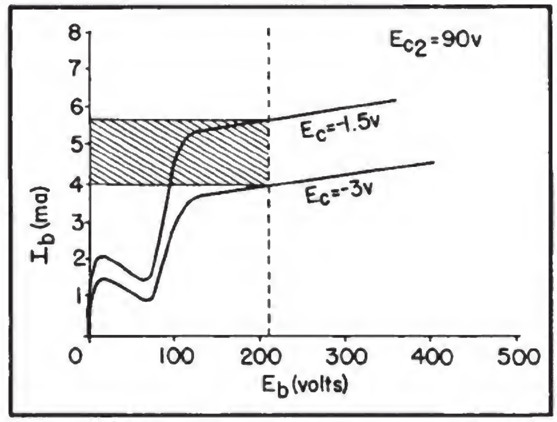

Figure 20-7 - Computing transconductance.

20-8. Tetrode Amplifier - Quiescent

Of the many types of bias available, the most common type chosen for use with a tetrode amplifier is self bias. Self bias is probably chosen because of its protective features. If the dc current through the tube increases, a greater voltage will be dropped across the cathode resistor. The voltage drop across the cathode resistor is developed in such a fashion as to cause the cathode to be positive with respect to the ground reference. The positive potential applied to the cathode causes the excess current in the tube to be reduced.

Another form of bias that may be used is fixed bias. Fixed bias may be provided by a battery or the dc power supply. The battery has a disadvantage because the bias voltage will decrease as the battery ages and loses its charge. Fixed bias voltages are usually provided by voltage divider networks in the power supply. Fixed bias will not provide circuit protection as described in connection with cathode bias.

Figure 20-8 shows a typical RC coupled tetrode amplifier with a resistive load. This type of amplifier is very similar in operation to the RC coupled triode amplifier that was discussed previously. Stage gain will be the major difference between these amplifiers.

The cathode resistor for the amplifier in Figure 20-8 is chosen to develop the required bias voltage. The current through the cathode resistor, R_k, is the sum of the plate current and the screen current and is known as SPACE

A4. Plate current would be severely reduced due to lack of accelerating potential.

A5. The r_p would be slightly higher because there would be a smaller change in plate current for a given change in plate voltage.

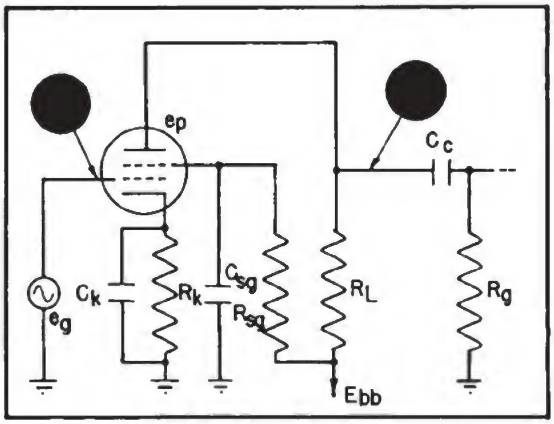

Figure 20-8 - RC coupled tetrode amplifier.

CURRENT, I_{space}. Space current is defined as the sum of the currents drawn by all of the positive elements in the tube. In the triode, for example, the space current would consist entirely of plate current, or could consist of both plate and control grid currents should the grid become positive.

The voltage developed across R_k may be determined by the following relationships:

$$E_{Rk} = (I_b + I_{c2})R_K$$

Normally, there are two current paths in the tetrode. There will be a current flow in the plate circuit and a current flow in the screen circuit. Applying Kirchhoff's voltage law to the plate circuit and the total plate current flow, the equation reads:

$$E_{bb} = (I_b + I_{c2})R_K + E_b + I_bR_L$$

Where E_{bb} is the supply voltage, I_b is the plate current, I_{c2} is the screen current, R_k is the cathode resistor in ohms, and I_bR_L is the voltage drop across the load resistor. The voltage E_b is plate voltage, and is always the potential difference between the plate and the cathode. It may also be viewed as the voltage developed across the plate supply minus the voltage developed across the load resistor and any voltage that may be developed across the cathode resistor. The coupling capacitor, C_c, and the grid resistor of the next tube form the coupling network through which the plate voltage variations of the tetrode are applied to the grid of the next stage. Since this network is connected across the tube, the coupling capacitor will charge to the quiescent value of plate voltage.

The other path for current is through the screen circuit. The equation for the complete loop of screen current is as follows:

$$E_{bb} = (I_b + I_{c2})R_k + E_{c2} + I_{c2}R_{sg}$$

Screen current will produce a voltage drop across the screen dropping resistor. The remaining voltage will be dropped between the screen grid and ground. Since the screen bypass capacitor is connected between the screen grid and ground, it will charge to the average screen voltage.

The analysis of quiescent conditions is now complete. All voltage drops have been accounted for and each capacitor has been charged to its normal potential. A signal may now be applied to the tube, and its operating condition analyzed.

Q6. Write the equation that may be used to determine the value of the cathode resistor. Assume that the voltage across the resistor is known.

20-9. Tetrode Amplifier (Signal Applied)

Figure 20-8 shows a tetrode amplifier with a signal applied. It is assumed that the tube is operated class A. The signal applied to the grid of the tube will cause the plate current and subsequent voltage drop across the load resistor to vary sinusoidally. The sine wave developed across the load resistor is the output of the amplifier. The output signal is coupled to the grid of the next tube through the RC coupling network. As the positive alternation of the applied signal decreases the negative control grid voltage, the space current through the tube increases. Due to the increased space current, more electrons strike the screen causing a rise in instantaneous screen current. The increased screen current produces a larger drop across the screen resistor causing a reduction in screen voltage. This somewhat counteracts the effects of the signal voltage upon the space current, resulting in degeneration. Knowing that degeneration is undesirable in the normal operation of an amplifier, a way must be found to minimize this adverse effect. This condition can be minimized in the same manner as in the cathode circuit of the triode amplifier by by-passing the resistor with a capacitor. A capacitor, C_{sg}, may be connected either from screen grid to the cathode, or from the screen grid to ground as shown in Figure 20-8. The latter method is the most common method used. If C_{sg} is made large enough, it will maintain the potential on the screen grid relatively constant for all normal values of signal voltages. The minimum value of capacitance which can be used is determined

in the same way as was the value of the cathode bypass capacitor.

$$C_{sg} = \frac{1}{2\pi f X_c}$$

Where $X_c = R_{sg}/10$ at the lowest frequency to be applied.

Therefore, the purpose of the screen bypass capacitor with its low impedance is to keep any ac variations from appearing between the screen grid and cathode.

PENTODES

20-10. Construction

The nonlinearity of a tetrode's characteristic curve (E_b-I_b) limits the use of the tube as an amplifier. Large input signals cause the tube to operate over the dynatron region of the characteristic curve resulting in a distorted output. To overcome the effects of secondary emission in tetrodes, a third grid called a SUPPRESSOR GRID is inserted between the plate and screen grid. This creates a five-element (PENTODE) tube. The location of these five elements is shown in Figure 20-9.

The physical construction of the suppressor grid is similar to that of the other grids. It differs only in that the mesh is usually more coarse. The effectiveness of the suppressor grid in reducing secondary emission is determined by the coarseness of its mesh. The finer the mesh, the more effectively it will reduce the passage of electrons from the plate to the screen grid. However, a fine suppressor grid mesh has the undesirable effect of limiting cathode-to-plate electron flow. Consequently a compromise is made in the construction of suppressor grids for optimum overall performance of the pentode.

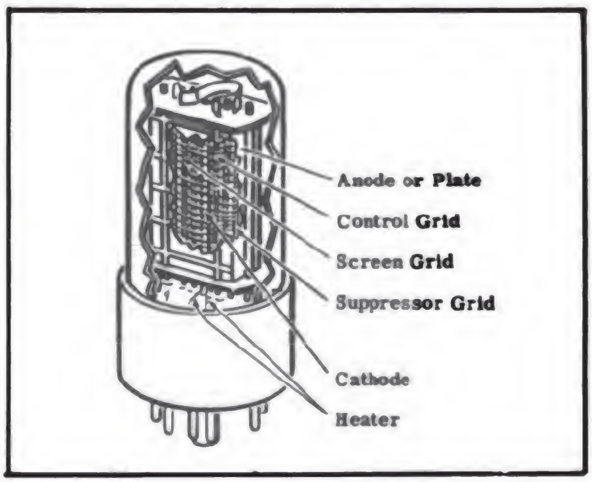

Figure 20-9 - Cutaway view of a pentode.

A secondary advantage obtained through the use of a suppressor grid is a further reduction in interelectrode capacitance. This increases the available gain and extends the frequency range beyond that of the tetrode.

20-11. Schematic Representation

The schematic symbol used to represent the pentode is shown in Figure 20-10. Note that there are two symbols shown. One symbol shows a type of pentode in which the suppressor grid connects to one of the pins on the base of the tube. The other shows the suppressor grid connected to the cathode inside the tube.

Connecting the suppressor grid to the cathode places it at zero potential with respect to the cathode, but at a negative potential with respect to the plate and screen grid. Being negative, the suppressor grid serves to repel or suppress secondary electrons from the plate. It also serves to slow down the primary electrons from the cathode as they approach the suppressor. These actions do not interfere with the flow of electrons from cathode to plate, but serve to prevent any interchange of secondary electrons between screen and plate. The suppressor, therefore, nearly eliminates the negative resistance effect which appears in the tetrode in the region where plate voltage falls below that of the screen. Thus, at any given grid voltage, plate current rises smoothly from zero to its saturation point as plate voltage is uniformly increased.

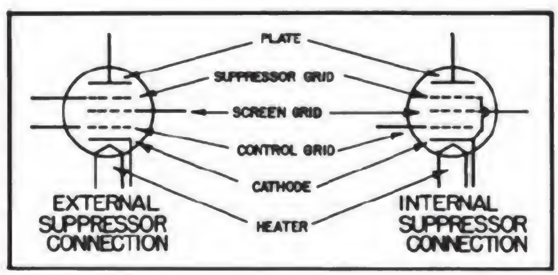

Figure 20-10 - Schematic representation of pentode tube.

CHARACTERISTIC CURVES

20-12. E_b-I_b Curves

Since the effects of secondary emission are eliminated by the action of the suppressor grid, the shape of the characteristic curve of a pentode differs considerably from that of a tetrode. In Figure 20-11 the plate family of curves for a 6SJ7 pentode is shown.

A6. $R_k = \dfrac{E_k}{I_b + I_{c2}}$

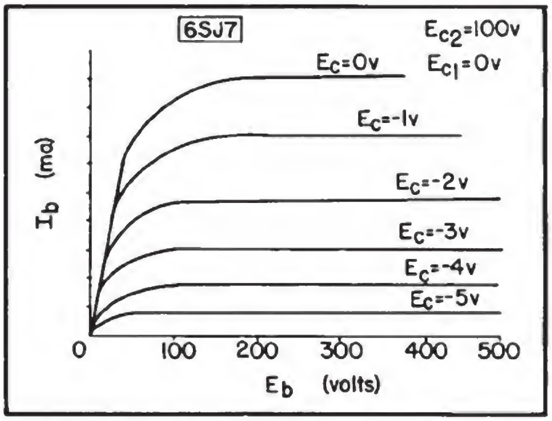

Figure 20-11 - Plate family of curves.

Notice that the dynatron region is absent, and that the plate potential can be changed several hundred volts without causing a substantial change in plate current. This results from the high degree of shielding provided by the screen and suppressor grids.

Since changes in plate voltage have little effect on plate current, the amplification factor and plate resistance of a typical pentode are high, being approximately 1600 and one megohm respectively for a 6SJ7. This makes possible a larger output signal with a given input signal as compared to triode amplifiers.

20-13. E_c-I_b Curves

Pentodes are often classified according to their E_c-I_b curves. Upon examination of the curve for a 6SJ7 pentode, it is apparent that the tube cuts off rather abruptly as the negative grid voltage is increased. A pentode having a curve of this shape is called a SHARP CUTOFF PENTODE.

Other pentodes, such as the 6SK7, approach cutoff very gradually requiring a substantial amount of bias to cause plate current cut-off. These tubes are called REMOTE CUTOFF or VARIABLE MU pentodes.

The remote cut-off characteristic is obtained through special construction of the control grid. A sharp cut-off tube has grid wires that are evenly spaced as shown for the 6SJ7 in Figure 20-12. To obtain a remote cut-off characteristic, the spacing of the grid wires must be non-uniform like those shown for the 6SK7 pentode. Notice that the grid wires are close together near the ends of the grid structure but widely spaced in the center.

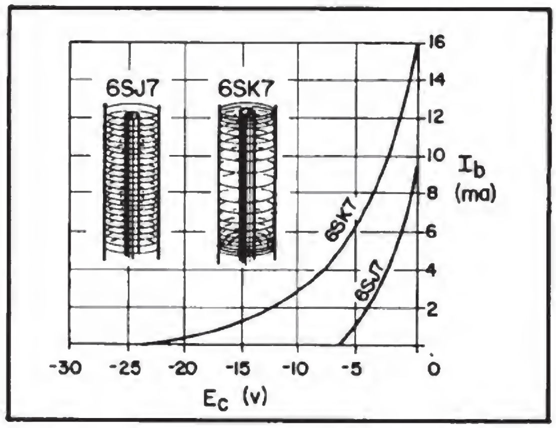

Figure 20-12 - Sharp and remote cutoff curves.

As the negative grid voltage applied to a remote cut-off tube is increased, a point is reached where the plate current flow through the ends of the grid structure is cut-off due to the greater control exercised by the more closely spaced wires. However, plate current still continues through the more widely spaced center section of the grid structure.

Since only the center section of the grid is now active in controlling plate current, the mu of the tube is lower because of the wider spacing of the wires in this area. Thus, the lower the operating point on the E_c-I_b curve, the lower the mu and the larger the change in grid voltage required to produce a given change in plate current.

PENTODE AMPLIFIER CIRCUIT

20-14. Circuit Description

A typical class A pentode amplifier suitable for amplification of audio frequencies within the range of 20 to 20,000 cps is shown in Figure 20-13. As in the triode amplifiers studied previously, the input signal (E_i) is applied between control grid and ground, and thus appears across the grid leak resistor R_1. The total grid voltage is the sum of the instantaneous signal voltage across the grid leak resistor and the dc bias voltage developed across the cathode resistor R_2.

Changes in plate current caused by the input signal produce voltage variations across R_4, the plate load resistor. These voltage variations represent an amplified and inverted reproduction of the input signal. Capacitor C_3 is used to couple the signal from the plate circuit of V_1 to the grid circuit of V_2, while at the same time preventing the appearance of a direct voltage across R_5.

The correct screen voltage is obtained by inserting voltage dropping resistor R_3 between the screen grid and the positive terminal of the power supply. In addition to voltage dropping, this resistor acts as a filter resistor. C_2 and R_3 form an "L" type filter which is used to maintain a constant dc potential between screen grid and cathode.

20-15. Quiescent Conditions

The quiescent or no signal conditions of the amplifier are shown in Figure 20-13. The complete plate circuit consists of R_2, the R_b of the tube, R_4, and supply voltage E_{bb}. Since this comprises a series circuit, the sum of the voltage drops must equal the source voltage, E_{bb}.

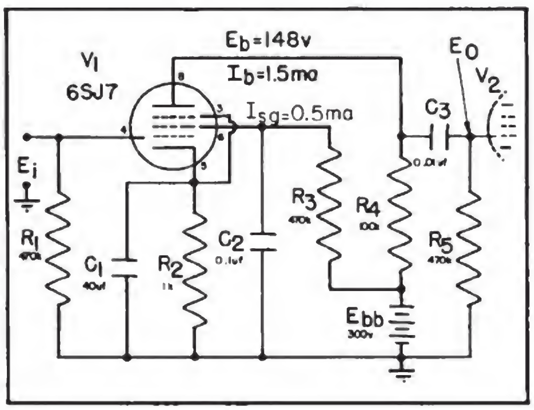

Figure 20-13 - Typical audio frequency voltage amplifier using a pentode tube.

With a plate current of 1.5 milliamps plate load resistor R_4 will drop 150 volts, and the remaining 150 volts will appear between plate and ground. Since cathode resistor R_2 carries 2 milliamps of current (I_b+I_{c2}), the cathode voltage with respect to ground is 2 volts. The plate voltage is therefore equal to the plate-to-ground voltage minus the cathode to ground voltage, or 148 volts.

The screen voltage can be found in a manner similar to that used for the finding plate voltage. The 0.5 milliamps of current flowing through screen dropping resistor R_3 causes a voltage drop of 235 volts across R_3. This leaves 65 volts between screen grid and ground, or an actual screen potential of 63 volts.

Under normal operating conditions no direct current flows through grid leak resistors R_1 and R_5, except for the minute and normally insignificant contact current. Since no direct current exists in grid leak resistor, R_1, the grid-to-ground voltage is zero and the grid-to-cathode voltage is equal to the drop across R_2. Thus, the control grid voltage is -2 volts.

Q7. List the voltages across C_1, C_2, and C_3 under quiescent conditions.

Q8. Describe the charge and discharge paths for C_1.

Q9. Describe the charge and discharge paths for C_2.

GAIN AND FREQUENCY RESPONSE

20-16. Pentode Equivalent Circuit

Although a significant amount of information can be obtained from a load line constructed on a plate family of curves, this method is inadequate where a complete analysis of an amplifier is desired. When large values of plate load resistance are employed, the load line becomes nearly horizontal, making interpretation of values difficult. Further limitations of graphical analysis become apparent when the effects of frequency, interelectrode capacitance, and other circuit reactances must be taken into consideration.

By developing an ac equivalent circuit for a pentode amplifier, the calculation of output voltage, gain, and phase shift at any frequency becomes possible. In Chapter 19, it was shown that a Thevenin's equivalent circuit could be used to analyze a triode amplifier. Due to the high plate resistance characteristic of most pentodes, a Norton's (constant current) equivalent circuit is more convenient for pentode amplifiers. A Norton's equivalent circuit can be derived rather easily from a Thevenin's equivalent circuit. Those desiring a review of Norton's theorem are directed to section 7-21:

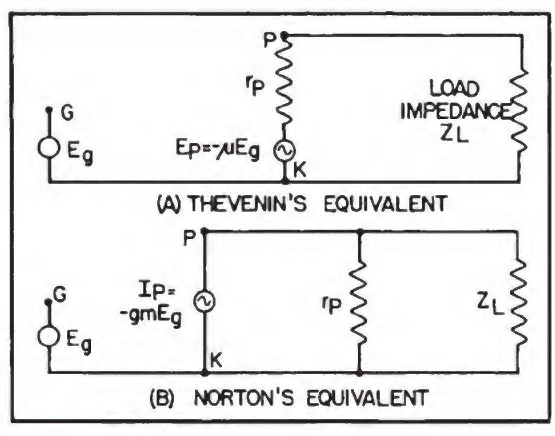

Figure 20-14 - Thevenin's and Norton's equivalent circuits for a vacuum tube amplifier.

Figure 20-14A shows the Thevenin's equiva-

A7. C_1 - 2 volts, C_2 - 65 volts, C_3 - 150 volts.

A8. Charge: From ground through C_1, through the plate and screen circuits, through R_3 and R_4 to B+, through E_{bb} to the bottom plate of C_1.
Discharge: From the bottom plate of C_1 through R_2 to the top plate of C_1.

A9. Charge: From ground through C_2, through R_3 to B+, through E_{bb} to ground.
Discharge: From the bottom plate of C_2 through the cathode bias network C_1R_2, through the tube from cathode to screen, to the top plate of C_2.

---

lent circuit generally used for the analysis of triode amplifiers. To construct a Thevenin's equivalent circuit for a vacuum tube amplifier, the tube is replaced by a generator and a series resistance. The generator is assumed to provide a constant RMS output voltage (E_p) equal to $-\mu E_g$; the minus sign indicating the output voltage to be inverted with respect to the input voltage (E_g). The r_p of the tube is placed in series with the generator and constitutes the losses within the tube. The load impedance (Z_L) is a complex quantity consisting mainly of resistance and capacitive reactance.

Notice that in comparing Thevenin's equivalent circuit for a vacuum tube to Thevenin's equivalent circuit for a dc network (section 7-18), the open circuit load voltage E_{th} is identical to $-\mu E_g$, and the impedance Z_{th} looking back from the load is identical to r_p.

To construct a Norton's equivalent circuit the tube is replaced with a constant current generator. According to Norton's theorem, the current produced by this constant current generator is equal to the current that would flow through a short placed across the load terminals. Placing a short across the load in Figure 20-14B connects r_p directly across the generator $-\mu E_g$. The current which flows in this short is the same as the current which flows through r_p and can be found by Ohm's law.

$$I = \frac{E}{R}$$

$$i_p = \frac{-\mu E_g}{r_p} \qquad (20\text{-}2)$$

In Chapter 19 it was stated that a relationship exists between amplification factor (μ), transconductance (gm), and plate resistance (r_p). This relationship can be stated as:

$$gm = \frac{\mu}{r_p} \qquad (19\text{-}9)$$

If gm is substituted for μ / r_p in equation (20-2) equation (20-3) results.

$$i_p = -\,gm\,E_g \qquad (20\text{-}3)$$

Thus, Norton's current is equal to $-gmE_g$. To complete Norton's equivalent circuit, the r_p of the tube and the load impedance are connected in parallel with the constant current generator as shown in Figure 20-14B.

20-17. Complete Equivalent Circuit

The complete equivalent circuit for a vacuum tube amplifier must take into consideration any resistances and reactances that will affect the amplification of a signal. Assuming that the cathode and screen resistances are properly bypassed, the equivalent circuit shown in Figure 20-15 accurately represents the pentode amplifier for which it is constructed. Although this circuit represents a vacuum tube amplifier, its solution should be a familiar one, since series-parallel networks were discussed at length in Chapter 13. It must be admitted, however, that the solution of the complete equivalent circuit shown in Figure 20-15 (complete Norton's equivalent circuit) would be a long and tedious one which the technician would hesitate to tackle. Fortunately, the solution of the complete equivalent circuit need not be attempted, since simplifications can be made under certain conditions. By treating the amplifier circuit one frequency at a time, certain components of the complete equivalent circuit can be neglected leading to a less complex network.

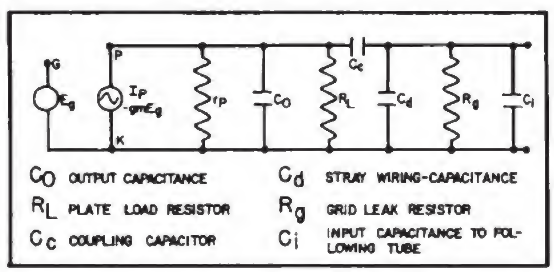

Figure 20-15 - Complete Norton's equivalent circuit for one stage of a pentode amplifier.

20-18. Mid-band Equivalent Circuit

Audio amplifiers are called upon to amplify frequencies within the audio spectrum of 20 to 20,000 cps. The complete audio spectrum can be divided, for purposes of analysis, into three

bands called: the high frequency band, the mid-frequency band, and the low frequency band. To determine the characteristics of an amplifier in the mid-band frequency range a signal frequency of 1,000 cps will be used. This frequency is chosen because it is near the geometric mean of the audio spectrum, and is, therefore, representative of this band of frequencies.

At a frequency of 1,000 cps, the coupling capacitor (C_c) of a properly designed amplifier has a reactance low enough to be considered a short circuit. The capacitor can thus be omitted from the mid-band equivalent.

The shunt capacitances (C_o, C_i, and C_d) in Figure 20-15, caused by the tube and connecting wires ordinarily have a combined value of less than 50 pf. These capacitances have such a high reactance at 1,000 cps that they can be considered as open circuits.

Since the series and shunt capacitances can be neglected at a frequency of 1,000 cps, the mid-band equivalent circuit shown in Figure 20-16 contains only resistance. The current "$-gmE_g$" has been written as $gmE_g\underline{/180^\circ}$ to more clearly indicate the phase reversal between grid and plate circuits.

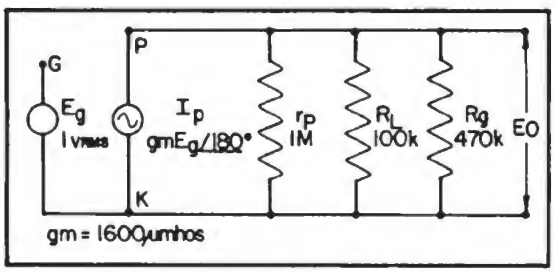

Figure 20-16 - Equivalent circuit with values included.

20-19. Mid-band Output Voltage and Gain

Once the equivalent circuit has been developed, the magnitude and phase of the output voltage and the stage gain can be computed. To illustrate this procedure, the gain of the amplifier shown previously in Figure 20-13 will be computed. The mid-band equivalent circuit for this amplifier is shown in Figure 20-16.

Notice that the input voltage to the amplifier is 1 volt RMS and is symbolized as E_g. The output voltage, also an RMS value, is taken across the grid leak resistor of the following stage and is symbolized as E_o. The output voltage can be found by Ohm's law as follows:

$$E_o = I_p R_{eq}\underline{/180^\circ} \qquad (20\text{-}4)$$

where: E_o = RMS output voltage
I_p = RMS component of plate current
R_{eq} = combined resistance of r_p, R_L, and R_g in parallel

The equivalent resistance of three resistance in parallel can be found by the reciprocal formula or by the product over the sum method. The product over the sum formula for three parallel resistors is:

$$R_{eq} = \frac{R_1R_2R_3}{R_1R_2+R_1R_3+R_2R_3}$$

Substituting for I_p and R_{eq} in equation (20-8)

$$E_o = gmE_g\underline{/180^\circ} \times \frac{r_pR_LR_g}{r_pR_L + r_pR_g + R_LR_g}$$

Substituting values from the equivalent circuit

$$E_o = (1600\times10^{-6})\frac{4.7 \times 10^{16}}{6.17 \times 10^{11}}$$

$$E_o = 122\underline{/180^\circ} \text{ volts RMS}$$

The above computation shows that the output voltage for those frequencies near the center of the amplifier's range would be 122 volts for a one volt input signal. The computations also show that, except for the 180° polarity inversion, no phase shift occurs during amplification of the mid-band frequencies.

Once the output signal amplitude is known, the gain of the amplifier can be calculated using equation (20-5).

$$A_m = \frac{E_o}{E_i} \qquad (20\text{-}5)$$

where: A_m = the mid-band gain
E_o = the output voltage
E_i = the input voltage in the same units (peak, RMS, etc.) as E_o

Using this formula, the mid-band gain of the amplifier under discussion is:

$$A_m = \frac{E_o}{E_i} \qquad (20\text{-}5)$$

$$A_m = \frac{122}{1}$$

$$A_m = 122$$

In many cases only the gain figure of the amplifier is required. A gain formula in which the output voltage is not required can be de-

rived as follows:

$$E_o = I_p R_{eq} \underline{/180^\circ} \qquad (20\text{-}4)$$

Substituting for I_p:

$$E_o = gmE_g R_{eq} \underline{/180^\circ}$$

Dividing both sides by E_g:

$$\frac{E_o}{E_g} = \frac{gmE_g R_{eq} \underline{/180^\circ}}{E_g}$$

Since gain $A_m = E_o/E_g$:

$$A_m = gmR_{eq} \underline{/180^\circ} \qquad (20\text{-}6)$$

Q10. How would an increase in the resistance of R_L affect the gain of an amplifier?

20-20. Low Frequency Equivalent Circuit

To investigate the operation of a pentode amplifier at the low frequency end of the audio spectrum, a low frequency equivalent circuit can be constructed. At the low end of the audio spectrum, the reactances of C_o, C_i, and C_d will be higher than at the mid-band frequencies; and again these capacitances can be neglected. On the other hand, the coupling capacitor, C_c, is in series with the output terminals of the amplifier and must be taken into consideration. As the frequency of the signal decreases, the reactance of the coupling capacitor rises causing more signal voltage to drop across the coupling capacitor and less signal voltage to develop across the grid leak resistor of the following stage. Thus, at low frequencies the coupling capacitor can no longer be considered as a short to the signal. The low frequency equivalent circuit for a pentode amplifier showing the electrical location of the coupling capacitor is illustrated in Figure 20-17. The part values used in the equivalent circuit are the same as those used previously.

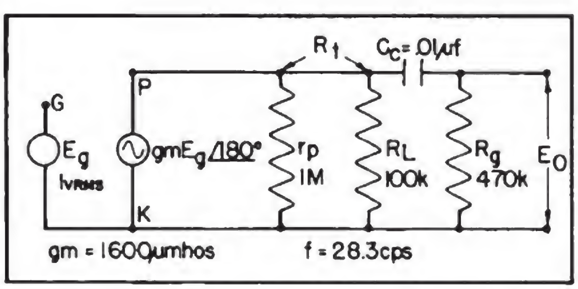

Figure 20-17 - Low frequency equivalent circuit.

20-21. Determining Low Frequency Gain

Once the equivalent circuit is derived, formulas can be developed to obtain the output voltage and gain at any frequency below the mid-band frequencies. In the following example the gain of the amplifier will be computed for a frequency of 28.3 cps using equation (19-20). The derivation of this equation is somewhat complex, and, therefore, is not shown here. However, the derivation is included at the end of this chapter for those interested.

$$A_{lf} = \frac{gm\, R_t R_g \underline{/180^\circ}}{R_t + R_g - jX_{cc}} \qquad (19\text{-}20)$$

where: A_{lf} = the low frequency gain
gm = tube transconductance
R_t = equivalent resistance of r_p and R_L in parallel
R_g = resistance of the grid leak resistor
X_{cc} = reactance of the coupling capacitor at the frequency at which the gain is to be computed.

Before equation (19-20) can be solved, R_t and the reactance of the coupling capacitor at the desired frequency must be computed. These are:

$$R_t = \frac{r_p R_L}{r_p + R_L}$$

$$R_t = \frac{(1\times10^6)(0.1\times10^6)}{1.1\times10^6}$$

$$R_t = 91{,}000 \text{ ohms approx.}$$

and

$$X_{cc} = \frac{1}{2\pi f C_c}$$

$$X_{cc} = \frac{1}{6.28\times28.3\times0.01\times10^{-6}}$$

$$X_{cc} = 560{,}000 \text{ ohms approx.}$$

Inserting the proper values into equation (19-20) and solving for the gain:

$$A_{lf} = \frac{gmR_t R_g \underline{/180^\circ}}{R_t + R_g - jX_{cc}} \qquad (19\text{-}20)$$

$$A_{lf} = \frac{(1600\times10^{-6})(0.09\times10^6)(0.47\times10^6) \underline{/180^\circ}}{(0.09\times10^6)+(0.47\times10^6)+(-j\,0.561\times10^6)}$$

$$A_{lf} = \frac{67.7 \times 10^6 \angle 180^\circ}{(0.561\times10^6) - j\,(0.561\times10^6)}$$

Convert the denominator to polar form. The phase angle of the denominator is:

$$\theta = \arctan \frac{-j\,0.561\times10^6}{0.561 \times10^6}$$

$$\theta = -45^\circ$$

The polar magnitude of the denominator is:

$$M = \frac{-jX_{cc}}{\sin\theta}$$

$$M = \frac{0.561 \times 10^6}{0.707}$$

$$M = 0.795 \times 10^6$$

$$A_{lf} = \frac{(67.7 \times 10^6) \angle 180^\circ}{(0.795\times10^6) \angle -45^\circ}$$

$$A_{lf} = 85 \angle 225^\circ$$

Thus, the gain of the amplifier at a frequency of 28.3 cps is 85. Notice that the output signal has been shifted 45° in phase in addition to the 180° polarity inversion caused by the tube.

If the gain at 28.3 cps (85) is compared to the gain at a mid-band frequency of 1,000 cps (122), the gain at 28.3 cps is seen to be 70.7% of the mid-band gain. At this low frequency the output voltage of the amplifier falls to 70.7% of its mid-band value, and the output power drops to one-half its maximum value. The frequency at which this occurs (28.3 cps for this amplifier) is called the LOWER HALF-POWER FREQUENCY. This frequency is designated "f_1".

Notice that at the lower half-power frequency, f_1, the reactance of the coupling capacitor has risen to a value of 560,000 ohms. At f_1 THE REACTANCE OF THE COUPLING CAPACITOR IS EQUAL TO THE SUM OF THE GRID LEAK RESISTANCE AND THE EQUIVALENT RESISTANCE OF r_p AND R_L IN PARALLEL ($X_{cc} = R_g + R_t$).

Q11. If R_g is reduced in value, what will happen to the lower half-power point?

20-22. High Frequency Equivalent Circuit

The high frequency characteristics of an amplifier can be analyzed by developing a high frequency equivalent circuit. In this equivalent circuit, the coupling capacitor is omitted since its reactance is negligible. The shunt reactances of C_o, C_i, and C_d cannot be neglected, however, because these reactances are in parallel with the load resistance of the tube. At high frequencies, the low reactance of this shunt capacitance lowers the load impedance and reduces the gain. As shown in Figure 20-18 the high frequency equivalent circuit consists of r_p, R_L, R_g, and C_s in parallel. C_s represents the combined capacitance of C_o, C_i, and C_d.

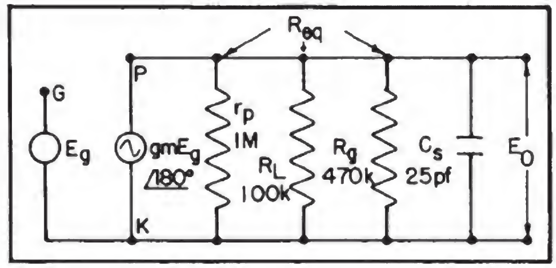

Figure 20-18 - High frequency equivalent circuit.

20-23. Determining High Frequency Gain

To demonstrate the high frequency characteristics of the amplifier, the gain will be computed for a frequency of 83.5 kilocycles. The gain equation, shown below as equation (19-21), is obtained from the high frequency equivalent circuit. The derivation of this equation is included at the end of the chapter.

$$A_{hf} = \frac{(gmR_{eq}\angle 180^\circ)\,(X_{cs}\angle -90^\circ)}{R_{eq} - jX_{cs}} \qquad (19\text{-}21)$$

where: A_{hf} = the high frequency gain
R_{eq} = the combined resistance of r_p, R_L, and R_g in parallel
X_{cs} = total reactance of C_o, C_i, and C_d

Values of X_{cs} and R_{eq} are obtained first.

$$X_{cs} = \frac{1}{2\pi f C_s}$$

$$X_{cs} = \frac{1}{6.28 \times 83.5 \times 10^2 \times 25 \times 10^{-12}}$$

X_{cs} = 76,100 ohms approx.

and:

$$R_{eq} = \frac{r_p R_L R_g}{r_p R_L + r_p R_g + R_L R_g}$$

$$r_p R_L = 1\times10^6 \times 0.1\times10^6 = 0.1 \times 10^{12}$$

$$r_p R_g = 1\times10^6 \times 0.47\times10^6 = 0.47 \times 10^{12}$$

$$R_L R_g = 0.1\times10^6 \times 0.47\times10^6 = 0.047 \times 10^{12}$$

A10. The gain would increase since an increase in R_L would cause an increase in R_{eq}.

A11. The half-power point will occur at a higher frequency.

$$R_{eq} = \frac{1\times10^6 \times 0.1\times10^6 \times 0.47\times10^6}{(0.1\times10^{12})+(0.47\times10^{12})+(0.047\times10^{12})}$$

$R_{eq} = 76,100$ ohms approx.

$$A_{hf} = \frac{(gmR_{eq}\angle 180^\circ)(X_{cs}\angle -90^\circ)}{R_{eq} - jX_{cs}} \qquad (19\text{-}21)$$

$$A_{hf} = \frac{(1600\times10^{-6}\times76.1\times10^3 \angle 180^\circ)(76.1\times10^3\angle -90^\circ)}{(76.1 \times 10^3) + (-j76.1 \times 10^3)}$$

Convert the denominator to polar form. The phase angle of the denominator is:

$$\theta = \arctan \frac{-j76.1\times10^3}{76.1 \times 10^3}$$

$$\theta = -45^\circ$$

The polar magnitude of the denominator is:

$$M = \frac{-jX_{ct}}{\sin\theta}$$

$$M = \frac{76.1 \times 10^3}{0.707}$$

$$M = 107.8 \times 10^3$$

Writing the denominator in polar form and simplifying:

$$A_{hf} = \frac{9265.9 \times 10^3 \angle 90^\circ}{107.8 \times 10^3 \angle -45^\circ}$$

$$A_{hf} = 86\angle 135^\circ$$

Notice that again the amplifier gain has dropped to 70.7% of the mid-band gain. Since the output power is proportional to the square of the output voltage, the output power will be one-half the mid-band value. This frequency of 83.5 kilocycles is called the UPPER HALF-POWER FREQUENCY (f_2) for this particular amplifier.

A comparison of the results of the three previous gain calculations shows that the response of the amplifier is maximum for those frequencies which lie near the center of the audio spectrum, but decreases greatly at very low frequencies. This amplifier would be considered useful for all frequencies between f_1 and f_2.

Q12. What would happen to the high frequency response of an amplifier stage if resistor R_L were reduced in value?

DERIVATION OF GAIN EQUATIONS

20-24. Low Frequency Gain

The low frequency gain equation is derived using the equivalent circuit in Figure 20-17.

Resistances r_p and R_L are combined into one equivalent resistance R_t.

$$R_t = \frac{r_p R_L}{r_p + R_L} \qquad (1)$$

Using the voltage divider formula an equation is set up for the output voltage (E_o) in terms of the voltage across R_t.

$$E_o = \frac{E_{R_t} R_g}{R_g - jX_{cc}} \qquad (2)$$

Using the current divider formula the current I_{Rt} through R_t is:

$$I_{Rt} = \frac{(gmE_g\angle 180^\circ)(R_g - jX_{cc})}{R_t + R_g - jX_{cc}} \qquad (3)$$

By Ohm's law the voltage across R_t is:

$$E_{Rt} = \frac{(gmE_g\angle 180^\circ)(R_g - jX_{cc})\, R_t}{R_t + R_g - jX_{cc}} \qquad (4)$$

Substituting (4) into equation (2):

$$E_o = \frac{\dfrac{(gmE_g\angle 180^\circ)(R_g - jX_{cc})R_t R_g}{R_t + R_g - jX_{cc}}}{R_g - jX_{cc}} \qquad (5)$$

Simplifying:

$$E_o = \frac{(gmE_g\angle 180^\circ)(R_g - jX_{cc})R_t R_g}{R_t + R_g - jX_{cc}} \times \frac{1}{R_g - jX_{cc}}$$

$$E_o = \frac{gmE_g R_t R_g \angle 180^\circ}{R_t + R_g - jX_{cc}} \qquad (6)$$

Dividing both sides of equation (6) by E_g:

$$\frac{E_o}{E_g} = \frac{\dfrac{gmE_gR_tR_g \angle 180^\circ}{R_t + R_g - jX_{cc}}}{E_g} \qquad (7)$$

Since E_o/E_g represents gain, simplifying (7) yields:

$$A_{lf} = \frac{gmR_tR_g \angle 180^\circ}{R_t + R_g - jX_{cc}} \qquad (19\text{-}20)$$

20-25. High Frequency Gain

The high frequency gain equation is derived using the equivalent circuit in Figure 20-18.

Resistances r_p, R_L, and R_g are combined into one equivalent resistance R_{eq}. The impedance of the network is equal to R_{eq} in parallel with the total shunt capacitance C_t.

$$Z = \frac{(R_{eq})(-jX_{cs})}{R_{eq} - jX_{cs}} \qquad (1)$$

The output voltage (E_o) is equal to the generator current ($gmE_g \angle 180^\circ$) multiplied by the network impedance.

$$E_o = \frac{(gmE_g \angle 180^\circ)(R_{eq})(-jX_{cs})}{R_{eq} - jX_{cs}} \qquad (2)$$

Dividing both sides by E_g, and simplifying:

$$\frac{E_o}{E_g} = \frac{\dfrac{(gmE_g \angle 180^\circ)(R_{eq})(-jX_{cs})}{R_{eq} - jX_{cs}}}{E_g} \qquad (3)$$

$$\frac{E_o}{E_g} = \frac{(gmR_{eq} \angle 180^\circ)(-jX_{cs})}{R_{eq} - jX_{cs}} \qquad (4)$$

Since gain is equal to E_o/E_g:

$$A_{hf} = \frac{(gmR_{eq} \angle 180^\circ)(X_{cs} \angle -90^\circ}{R_{eq} - jX_{cs}} \qquad (19\text{-}21)$$

A12. The high frequency response would improve, since f_2 would occur at a higher frequency.

EXERCISE 20

1. What limitations of the triode lead to the development of the tetrode?
2. Describe the construction of a tetrode vacuum tube.
3. What is the function of the screen grid?
4. What potential is applied to the screen grid?
5. What is the purpose of the screen dropping resistor?
6. What is the purpose of the screen bypass capacitor?
7. Compute the value of the screen dropping resistor if the screen current is 3.8 ma., the supply voltage is three hundred volts, and the desired screen voltage is 90 volts.
8. What limitation of the tetrode lead to the development of the pentode?
9. Describe the construction of a pentode vacuum tube.
10. What potential is normally applied to the suppressor grid?
11. Compare the plate resistances of typical triodes, tetrodes, and pentodes.
12. What effect would an insufficient value of screen bypass capacitance have on the low frequency gain of a pentode amplifier?
13. What would happen to the operation of a pentode amplifier if the screen bypass capacitor become shorted?
14. Using the circuits of Figures 20-16 and 20-17, compute the gain at frequencies of 45 cps, 10 kc, and 50 kc.
15. From the values of gain obtained in Question 14, plus the values from the three example problems in the chapter, draw a response curve for the amplifier in Figure 20-13. Plot frequency on the horizontal axis and gain on the vertical axis. Use a logarithmic scale for frequency.
16. Describe the characteristics that a pentode tube and coupling network should have to produce good low frequency response.
17. Describe the characteristics that a pentode tube and coupling network should have to produce good high frequency response.
18. Find the total load resistance required if the tube in Figure 20-16 was to have a mid-band gain of 48.
19. What would be the f_2 frequency for this value of load?
20. How does this f_2 compare to the f_2 for a 100K R_L?

CHAPTER 21

PARAPHASE AMPLIFIER CIRCUITS

This chapter will explain the purpose of paraphase amplifier circuits, as well as the operation of the basic types. Circuit configurations of each type will be shown and their advantages and disadvantages discussed.

21-1. Purpose of Paraphase Amplifier Circuits

Since phase is generally associated with time, it is somewhat of a misnomer to apply this term to a device that simply changes a positive-going signal to a negative-going signal or vice versa. In the case of a sine-wave signal, however, the effect is the same as if a 180° phase shift had occured.

Paraphase amplifiers (phase splitters) produce, from a single input waveform, two output waveforms that have exactly opposite instantaneous polarities. If these two waveforms were produced as the result of a single sine-wave input they might be considered 180° out of phase, one waveform appearing to have been displaced 180° along the time axis.

One type of phase inverter is the transformer, with which the instantaneous polarity of the load may be reversed with respect to the source by reversing either the connections of the secondary leads to the load or the primary leads to the source. A conventional electron-tube amplifier (untuned and RC coupled) also produces an output of opposite polarity to the input. Either single or two-tube amplifiers may be used to convert one input waveform into output waveforms of opposite polarity. Such amplifiers are called PHASE SPLITTERS or PARAPHASE amplifiers.

The outputs obtained from a paraphase amplifier fulfill the requirements necessary for the proper operation of certain electronic circuits. One such circuit is the push-pull amplifier (to be discussed in a future chapter). Figure 21-1 shows the block diagram of a paraphase amplifier connected to a push-pull amplifier. The single sine-wave input to the paraphase amplifier has been converted to two sine-waves, equal in amplitude but opposite in polarity. These two signals are used as the input to the push-pull amplifier. A paraphase amplifier used in this manner is known as a DRIVER.

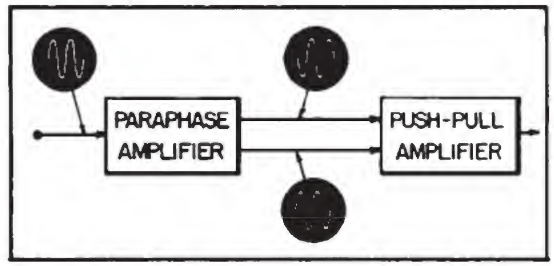

Figure 21-1 - Block diagram phase splitter and push-pull amplifier.

21-2. Transformer Phase Splitter

In operation, all transformers produce across the secondary an induced EMF that is opposed to the change in flux producing it. The instantaneous polarity of the actual output voltage across a load depends on how the leads from the secondary are connected.

Figure 21-2 indicates phase inversion of a sine wave. In actuality the polarity has simply

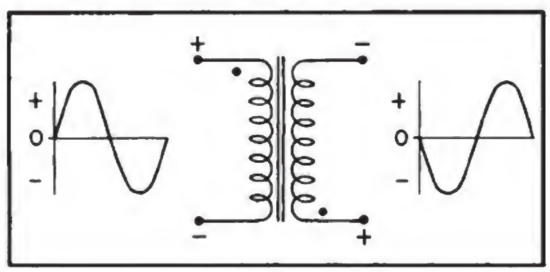

Figure 21-2 - Transformer phase inverter

been inverted, but, in some cases it is more convenient to refer to the inversion as a 180° phase shift—in effect, the same result as if the waveform had been moved along the time axis 180°.

The simplest method of obtaining two signals with equal magnitudes and opposite polarities, is by use of a transformer with a center tapped secondary winding. Figure 21-3 is used to explain the operation of this type of phase splitter.

When the input signal causes the polarity at point X to become negative with respect to the center tap, and point Y to become positive with

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respect to the center tap, two signals of opposite polarity will appear in the transformer secondary. Tapping the transformer secondary at its exact electrical center insures the two signals being of equal magnitude.

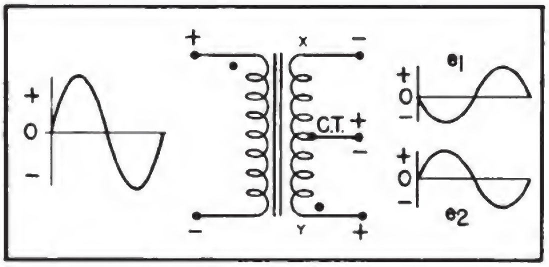

Figure 21-3 - Transformer phase splitter (center tapped secondary)

Another transformer phase splitter makes use of a center tapped resistor placed in shunt with the secondary winding rather than center tapping the winding itself. Figure 21-4 illustrates this method. The operation is the same as that of the center tapped secondary.

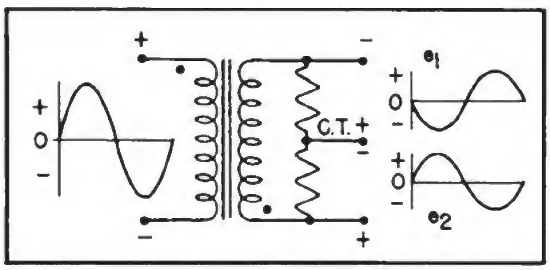

Figure 21-4 - Transformer phase splitter (center tapped resistor)

The transformer phase splitter has several disadvantages among which are its size and cost (compared to methods discussed in the following topics). The transformer phase splitter also has limited application because of distortion and losses inherent in transformers. For example, the loss in voltage through leakage reactance is greater for higher frequencies than it is for lower frequencies. The shunting capacitance effect and hysteresis losses also increase with frequency. Since in many circuits harmonics must be transmitted unattenuated and undistorted, the transformer phase inverter is generally replaced with a circuit that performs phase inversion without the use of transformers.

The electron tube phase splitter or paraphase amplifier is such a circuit.

An advantage of the transformer phase splitter is smaller power loss in the interstage coupling.

Q1. Explain the disadvantage of using a transformer as a phase splitter.

Q2. Explain the advantages of using a transformer as a phase splitter.

21-3. Electron-Tube Phase Inverter

Any electron tube used as a conventional amplifier has an output of opposite polarity to its input. In other words, a positive-going signal on the grid produces a negative-going signal at the plate. However, in most applications of the electron tube the signal at the plate has an amplitude greater than that of the input signal. If the electron tube is to be used simply as a means of reversing the polarity of a signal, without affecting the amplitude or shape of the applied voltage, some means must be found to reduce the amplification to a 1-to-1 ratio.

One common method of reducing the gain of an amplifier is to introduce degenerative or negative feedback by omission of the usual bypass capacitor across the cathode resistor (Figure 21-5). The degeneration occurs because the potential of the cathode rises as the grid potential rises, thus preventing the swing of voltage effective between grid and cathode from reaching the amplitude of the applied grid signal. If R_2 is made the proper value of resistance, the gain of the tube can be canceled, and the output voltage at the plate of V_1 is equal in amplitude to the input voltage at the grid.

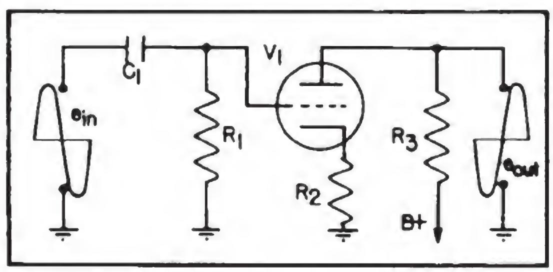

Figure 21-5 - Electron tube phase inverter employing cathode degeneration

21-4. Single Tube Paraphase Amplifier

One of the simplest forms of single tube parpahase amplifiers is shown in Figure 21-6. The input signal (E_{in}), going positive, causes the plate current to increase through the cathode load resistor, R_3, which results in a positive-going voltage across R_3. Resistor R_3 is coupled to the output load resistor, R_5, by capacitor C_3, which has a negligible reactance compared with the resistance of R_5 at the lowest signal

frequency to be amplified. Thus, the output voltage from the cathode side of the circuit is e_{o2}. In a similar manner, the rising plate current produces a negative-going voltage from plate to ground, which is coupled to the output load resistor, R_4, by capacitor C_2. The reactance of C_2 is negligable compared to the resistance of R_4 at the lowest frequency to be amplified. The output voltage from the plate side of the circuit is e_{o1}.

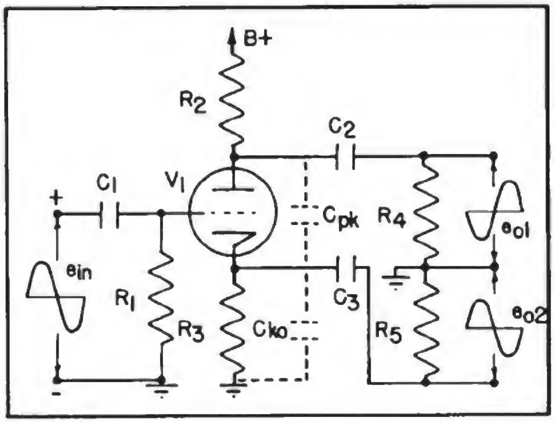

Figure 21-6 - Single tube paraphase amplifier

The two output voltages, e_{o1} and e_{o2}, are identical in magnitude and of opposite polarity, provided resistors R_2 and R_3 are identical and resistors R_4 and R_5 also are identical, as in the diagram. Thus, the amplifier V_1 acts as a perfect phase splitter in the circuit shown.

The balance of this phase splitter falls off at high frequencies. A reason for this is that resistors R_2 and R_3 are shunted by the unequal reactances of the interelectrode capacitances of the tube, C_{pk} and C_{ko}, shown by dashed lines. R_2 is shunted by the reactance of the plate-to-cathode capacitance, C_{pk}; R_3 is shunted by the reactance of the cathode-to-ground capacitance, C_{ko}. These two reactances load the resistors unequally, causing unbalanced output voltages at high frequencies.

The voltage gain of this paraphase amplifier (defined as e_{o1}/e_{in} and e_{o2}/e_{in}) is always less than unity, because the output voltage, e_{o2} appearing across the cathode load resistor, R_3 is always less than the input voltage, e_{in}. An explanation of this last statement will be made while referring to Figure 21-6.

An important point to understand is the fact that the sum of the signal voltage drops from grid to cathode, e_{gk}, and cathode to ground, e_{R3} are equal to the input signal voltage from grid to ground. Another point which should be realized is that the signal voltage from grid to cathode causes the change in plate current, developing the signal voltage across R_3. Stated another way, it is necessary to have a signal voltage developed between the grid and cathode in order to have a signal voltage developed across R_3. With these points in mind, it can be seen that the voltage developed across the cathode resistor, R_3 is equal to e_{in} minus e_{gk}. Consequently, e_{o2} will always be less than the input signal. Since e_{o1} and e_{o2} are identical, e_{o1} will always be less than e_{in}.

To enable this circuit to deliver the maximum output signals (approaching the magnitude of the input) the values of the plate load and cathode load resistors will have to be large. When this is done the bias will be too large for proper operation of the amplifier, since the amount of bias is dependent upon the value of the cathode resistor. Therefore, there is a need for a more practical circuit.

The single tube paraphase amplifier shown in Figure 21-7 differs somewhat from the amplifier shown previously. The dc grid bias in Figure 21-7 is obtained across only a portion of the total cathode resistance, R_3; the ac output voltage is taken from the cathode load resistor, R_6, which is equal to the value of the plate load resistor, R_2.

This circuit is useful when the total dc drop between cathode and ground exceeds the dc bias required for proper operation of the tube. Assume, for example, that the dc drop from cathode to ground is 100 volts, that the required bias is -10 volts, and R_6 must have a resistance of 90, 000 ohms. The proper value of bias is obtained by using 10, 000 ohms for R_3. With these values of resistances, and since the grid resistor is connected to the top of R_6, the dc voltage from grid to ground is 90 volts. Since the dc voltage from cathode to ground is 100 volts, the grid is a -10 volts in respect to the cathode. Due to this improved method of ob-

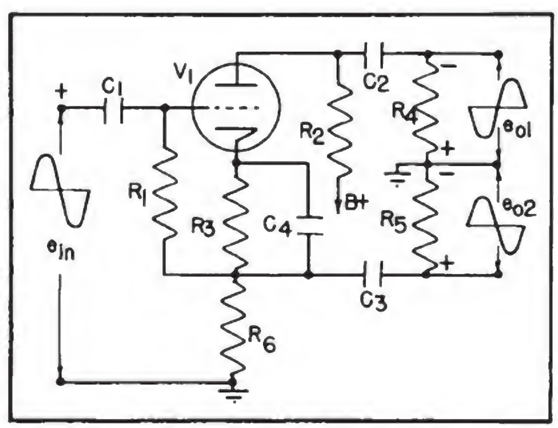

Figure 21-7 - Modified single tube paraphase amplifier.

A1. Poor frequency response, large size, cost.

A2. Simplest method and less power loss than other methods.

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taining bias, large values of load resistors are used to obtain output voltages as nearly equal in amplitude to the input voltage as possible.

The primary disadvantage of single tube paraphase amplifiers is that there is no amplification of the signal voltage.

Q3. What is the phase relationship between the voltage developed across the cathode resistor and the input signal? (Figure 21-6).

Q4. Referring to Figure 21-6, what would happen to the outputs if R_2 became shorted?

21-5. Two-Tube Paraphase Amplifier

Figure 21-8 shows a TWO-TUBE PARAPHASE AMPLIFIER circuit which provides greater gain than the single-tube paraphase amplifiers. Tubes V_1 and V_2 split the signal input voltage, e_{in}, into two opposite-going output voltages e_{o1} and e_{o2}. Tube V_1 acts as a conventional RC coupled amplifier. Tube V_2 is a combined phase inverter and amplifier having the same gain as V_1. V_1 develops a large, inverted voltage, e_{o1}, across R_6 and R_7 when a small signal voltage, e_{in}, is applied to its grid. The second output voltage, e_{o2}, is generated by supplying the grid of V_2 with a portion of the output voltage of V_1, that is, a small fraction of e_{o1} is obtained from a voltage divider consisting of R_6 in series with R_7. The resistance of R_7 is such that the grid voltage, e_{c2}, applied to V_2, has exactly the same magnitude as grid voltage e_{in}, applied to V_1. Under this condition, if the two amplifier circuits are otherwise identical, V_1 and V_2 develop two equal output voltages, e_{o1}, and e_{o2}, which are equal in amplitude but of opposite polarity.

For a numerical example of the operation of this circuit, assume that V_1 and V_2 each has a gain of 30, R_8 has a resistance of 30,000 ohms, and the resistance of the combination of R_6 plus R_7 also is 30,000 ohms. Output voltage e_{o1} is 30 volts, if e_{in} is 1 volt. Therefore, grid voltage e_{c2} should be 1 volt since the two grid voltages, e_{c1} and e_{c2}, must be identical in order to produce identical output voltages. If R_7 is equal to 1000 ohms or 1/30 of the total resistance of R_6 and R_7, then 1/30 of the total voltage e_{o1} or 1 volt will be applied to the grid of V_2. Triodes are most often preferred to pentodes in this circuit. A pentode usually has a high gain, and therefore only requires a small input voltage, a requirement which makes the size of R_7 too critical for practical applications.

This two-tube paraphase amplifier has some disadvantages. One is that the circuit can be balanced perfectly over only a narrow range of frequencies. This is because phase shift is introduced at the low and high frequency ends of the band. For example, at high frequencies, phase shift is caused by the shunt reactances of stray capacitances across the output circuit of V_1. At low frequencies, phase shift is caused by the series reactance of coupling capacitor C_4. These effects are multiplied in the output of V_2, because its output circuit is also shunted by stray capacitance, which results in phase shifts at high frequencies. The series reactance of coupling capacitor C_5 results in phase shift at low frequencies. Thus, the undesirable phase shift between e_{o1} and e_{o2} is considerable at low and at high frequencies.

The output voltage, e_{o2}, has more amplitude distortion than e_{o1}, because tubes V_1 and V_2 are effectively connected in cascade (coupled from plate to grid). Thus, the distortion produced by V_1 is fed to V_2, which amplifies and distorts it an additional amount because of its own non-linear operating characteristics.

Q5. If the gain of V_2 (Figure 21-8) were 17 and R_8 has a value of 255K ohms, find the value of R_7.

Q6. Why is the signal voltage e_{o2} (Figure 21-8) of opposite polarity in respect to e_{o1}?

Q7. What is the average dc potential across the output terminals e_{o1}? Why?

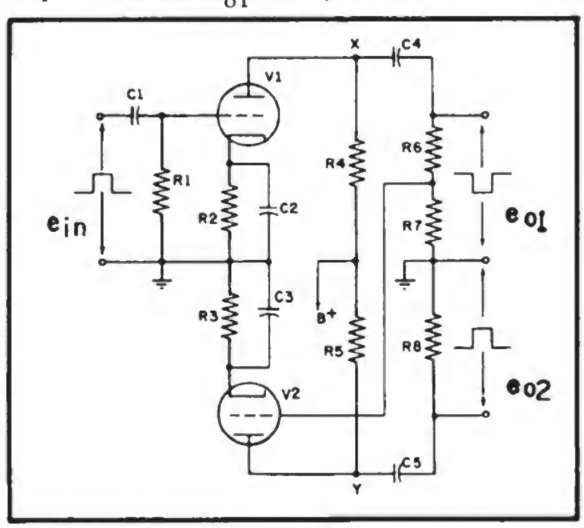

Figure 21-8 - Two-tube paraphase amplifier.

EXERCISE 21

1. Why is it necessary to have paraphase amplifiers?
2. What is the simplest method of obtaining paraphase operation?
3. How does a single tube generate two outputs equal in amplitude and of opposite polarity?
4. What is meant by the term "phase splitter"?
5. Why are the outputs of a single tube paraphase amplifier smaller in amplitude than the input?
6. What are the advantages of a single tube paraphase amplifier compared with a transformer?
7. Describe the dynamic operation of a two-tube paraphase amplifier.
8. What is the advantage of a two-tube paraphase amplifier compared with a single tube type?
9. What disadvantages are encountered in a two-tube paraphase amplifier?
10. Compare the operation of a two-tube and a single tube paraphase amplifier.
11. What is the function of the voltage divider used in a two-tube paraphase amplifier circuit?
12. How is bias achieved in paraphase amplifier circuits?

A3. They are in phase, but the cathode signal is smaller in amplitude than the input signal.

A4. There would be no output across R_4 while the output across R_5 would remain practically unchanged.

A5. R_7 equals 15K ohms. Therefore, R_6 would equal 240K ohms.

A6. Because the outputs are taken from the plate circuits of two tubes connected in cascade.

A7. Zero volts. Because C_4 has charged to the average dc plate potential of V_1. As a result, no dc current will flow through R_6 and R_7.

CHAPTER 22

AUDIO POWER AMPLIFIER

The primary function of a power amplifier is to efficiently deliver power to a load. The load may be a speaker, an antenna, or any useful device that consumes power. Power amplifiers are used as output stages in public address systems, radio transmitters, receivers, and as driving stages in transmitters to name a few examples.

This chapter is concerned with only one type of power amplifier, the AUDIO POWER AMPLIFIER. This type is used for power amplification within the audio frequency range, such as delivering power to a loudspeaker in a receiver. RF power amplifiers used within the radio frequency range will be covered in Chapter 25.

Various types of tubes may be used as audio amplifiers, including power triodes, power pentodes, and BEAM POWER TUBES. These tubes may be operated as SINGLE-ENDED or as PUSH-PULL STAGES. Single-ended audio power stages may consist of single-tube amplifiers or two or more tubes connected in parallel. Such parallel-connected tubes provide a greater power output for a given input than do single tubes. Regardless of the particular circuit used, single-ended audio power amplifiers are operated class A only. On the other hand, push-pull audio power amplifiers may be operated class A, AB, or B and provide greater output power than the same two tubes connected in parallel. Due to the excessive distortion involved, audio power amplifiers are never operated in class C.

In this chapter, information is subdivided into two major subjects—single-ended and push-pull audio power amplifiers. Under the subject of single-ended amplifiers, consideration is given to various power tubes, their physical and electrical characteristics, and comparison of parameters. Typical single-ended circuits are analyzed regarding power, distortion, frequency response and efficiency.

The subject of push-pull amplifiers includes circuit requirements, dc and ac flow, balancing networks and circuit characteristics under various classes of operation.

SINGLE-ENDED POWER AMPLIFIER CHARACTERISTICS

22-1. Circuit Description

Figure 22-1 shows a basic single-ended power amplifier using a power triode driving a speaker. In this circuit, C_1 and R_1 form the input coupling network. C_1 blocks the dc component of the plate voltage of the previous stage while the ac component is developed across R_1. R_2 is used to develop cathode self-bias. C_2 keeps the voltage across R_2 relatively constant when an input signal is applied. T_1 is the output transformer acting as the plate load impedance and provides power transfer from the plate circuit to the speaker.

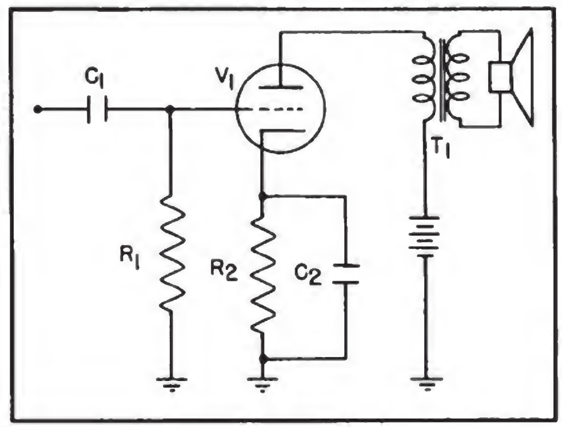

Figure 22-1 - Basic single-ended power amplifier.

The circuit differs from a voltage amplifier in the type of triode used and the function of the plate transformer.

22-2. Electrical Characteristics of the Power Triode

In audio power amplifiers, a large power output is of more importance than the voltage gain; therefore, voltage gain possibilities are sacrificed in the design of power triode tubes to obtain high-power handling capabilities. In general, power triodes have low amplification factors, low plate resistance, and high plate current. In order to obtain low plate resistance, the space between the plate and cathode is smaller in power tubes than in a voltage amplifier tube. Also, in a power tube the area of the plate is made larger and the cathode is designed to supply a larger number of electrons. The grid must not block too many electrons from flowing to the plate so the grid mesh is widely separated, which reduces the amplification factor. The

electrodes of a power tube are larger than those found in most voltage tubes since larger currents will be encountered in power amplifiers.

In Figure 22-2 is shown the plate family of curves for a 6C5 voltage triode and the 2A3 power triode. A comparison of the curves shows that a much larger grid voltage is required to operate the power triode. It is for this reason that one or more stages of voltage amplification are usually necessary to operate the power amplifier.

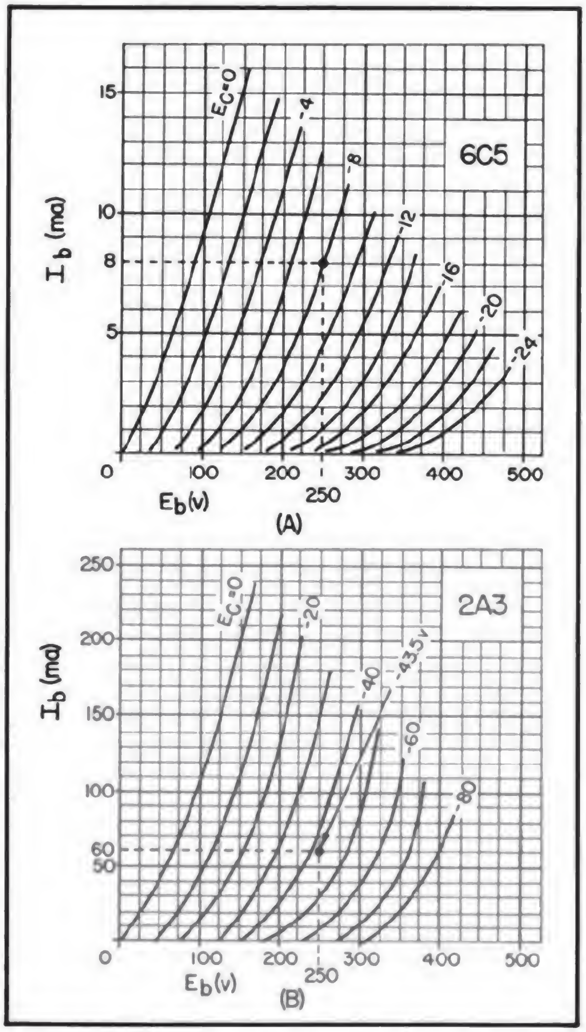

Figure 22-2 - (A) E_b - I_b curves for the 6C5 voltage triode. (B) E_b-I_b curves for the 2A3 power triode.

If both tubes are operated class A with a plate voltage of 250 volts, a comparison of the tube parameters can be made. Under typical operation, the 6C5 has an amplification factor of 20, a plate resistance of 10,000 ohms and a transconductance of 2000 micromhos. On the other hand, a 2A3 power triode has an amplification factor of 4.2, a plate resistance of 800 ohms, and a transconductance of 5250 micromhos. Of more interest is the plate current for the above values. The 6C5 plate current is only 8 ma. but the 2A3 has a plate current of 60 ma. The plate family of curves for the 2A3 power triode will be used throughout this chapter for an explanation of the triode power amplifier.

Q1. Why do power triodes have lower amplification factors than triodes used for voltage amplification?

22-3. Impedance Matching Transformer

To transfer maximum power to a load, as explained in Chapter 6, the load impedance must equal the source impedance. In audio power stages used to drive a speaker, the plate resistance of the tube, which is usually several hundred ohms, is the source impedance. The load impedance is that of the speaker, which is usually from 4 to 16 ohms. If this load were connected directly to the plate of a power amplifier having a large ac plate resistance, the transfer of power to the load would be small. Therefore, a means to improve the power transfer to the load must be developed. This is the purpose of the IMPEDANCE MATCHING TRANSFORMER. The transformer will match the impedance of the load to the impedance of the source. To understand how a transformer can be used to match impedances, a review of the ideal transformer, as developed in Chapter 15, will be given.

In Chapter 15, it was explained that the current flow through the primary of a transformer is very small when the secondary is open. Under such a condition, the primary impedance is very large. However, when a load resistance is connected to the secondary, the current that flows in the secondary produces a flux field which cancels some of the primary flux. This results in an increase in current drawn from the source trying to reestablish the original number of total flux lines. This effect of reflected impedance on primary current is the same as placing a physical resistor in shunt with the primary winding. In practical applications the inductive reactance of the primary winding will be at least 10 times greater than the reflected impedance of any resistive load connected to the secondary. Since the reflected impedance is in parallel with the inductive reactance of the primary winding, for all practical purposes the primary impedance is equal to the reflected impedance, which will be designated Z_p.

To establish the impedance ratio between transformer primary and secondary, a review

of voltage and current ratios will be given. Since the volts-per-turn in the primary is equal to the volts-per-turn in the secondary of an ideal transformer, the ratio of the primary to secondary voltage is the same as the ratio of primary to secondary turns, giving:

$$\frac{E_p}{E_s} = \frac{N_p}{N_s} \quad (15\text{-}6)$$

Since the flux which exists in the core of the transformer surrounds both primary and secondary and is proportional to the magnetizing force of the associated winding; the ampere turns (NI) is the same for both primary and secondary. Therefore:

$$N_p\, I_p = N_s\, I_s \quad (15\text{-}7)$$

and:

$$N_p/N_s = I_s/I_p \quad (15\text{-}8)$$

Combining equations (15-6) and (15-8) gives:

$$E_p/E_s = I_s/I_p \quad (15\text{-}9)$$

By cross-multiplication:

$$E_p\, I_p = E_s\, I_s$$

and:

$$P_p = P_s \quad (15\text{-}12)$$

The relationship of secondary load impedance (Z_s) and the reflected impedance (Z_p) of that load to the primary can be obtained from the above equations.

Since: $P_p = P_s$; and the general power formula is $P = I^2R$

Then:

$$I_p^2\, Z_p = I_s^2\, Z_s \quad (22\text{-}1)$$

which is the same as:

$$Z_p/Z_s = (I_s/I_p)^2 \quad (22\text{-}2)$$

Since:

$$N_p/N_s = I_s/I_p \quad (15\text{-}8)$$

by substitution:

$$Z_p/Z_s = (N_p/N_s)^2 \quad (22\text{-}3)$$

Transposing the above equation to solve for the reflected impedance (Z_p):

$$Z_p = (N_p/N_s)^2\, Z_s \quad (22\text{-}4)$$

From equation (22-4) it can be seen that the primary impedance of a transformer is dependent on the turns ratio and the secondary impedance. Therefore, with a given value of load impedance the reflected impedance can be made almost any value depending upon the turns ratio of the transformer chosen. For example, if a generator with an internal impedance of 40,000 ohms is to deliver maximum power to a 4-ohm load, the turns ratio of the transformer required to do this can be computed. From the maximum power transfer theorem, maximum power will be transfered to the secondary of the transformer when the primary impedance is equal to the internal impedance of the generator. Since this is an ideal transformer ($P_p = P_s$), maximum power is transfered to the load when $Z_p = 40,000$ ohms.

Solving for the turns ratio:

$$Z_p/Z_s = (N_p/N_s)^2 \quad (22\text{-}3)$$

Substituting for Z_p and Z_s:

$$\frac{40,000}{4} = \left(\frac{N_p}{N_s}\right)^2$$

Taking the square root of both sides:

$$\frac{N_p}{N_s} = \sqrt{\frac{40,000}{4}} = \frac{200}{2} = \frac{100}{1}$$

Therefore, the primary winding should have 100 turns for every turn in the secondary winding for maximum power transfer. It should be noted that even though power is being supplied to a 4-ohm load, this load appears as 40,000 ohms of impedance to the generator.

Q2. Find the reflected impedance of an 8-ohm load if the turns ratio of the transformer is 50:1.

22-4. Constructing a dc Load Line

A triode power amplifier circuit is shown in Figure 22-3, using a 2A3 power triode, cathode self-bias for class A operation, and an output transformer. The plate family of curves for the 2A3 is shown in Figure 22-4.

To establish the quiescent point on the plate family of curves, a dc load line and a cathode bias line are constructed. In the previous construction of a dc load line for voltage amplifiers, the two points which establish the line were the X intercept ($I_b = 0$, $E_b = E_{bb}$) and the Y intercept [$E_b = 0$, $I_b = E_{bb}/(R_L + R_k)$]. In this circuit, the X intercept is 225 volts and the Y intercept is 375 ma. As can be seen, the Y intercept is not within the range of values given on the family

A1. The power triode gridmesh is much larger, thereby reducing the effectiveness of the of the grid in controlling plate current.

A2. $Z_p = (N_p/N_s)^2 Z_s$ (22-4)

$Z_p = (50/1)^2 8 = 20,000$ ohms

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of curves. Another method to construct the load line must be used.

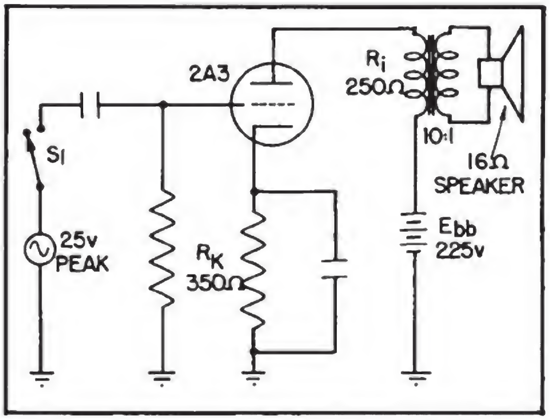

Figure 22-3 - Single-ended triode power amplifier.

By knowing the slope of the load line and one point, another point can be found so that the load line may be drawn through these two points. This is called the POINT-SLOPE METHOD. The known point (point A of Figure 22-4) is the X intercept where $I_b = 0$ and $E_b = 225$ volts, for this example.

The slope of the line is the reciprocal of the dc resistance, when the tube is considered as a short, or $-1/(R_i + R_k)$. R_i is the internal dc resistance offered by the primary of T_1 and R_k is the cathode resistor. The minus sign indicates the direction of the slope. The slope of the dc load line for the circuit shown in Figure 22-3 is -1/600.

The second point on the dc load line is found by converting the dc load line slope ($-1/(R_i + R_k)$ to a more usable form. If the slope is multiplied by the expression $\Delta I_b/\Delta I_b$, where ΔI_b means an incremental change in plate current, the result is a ratio of incremental change in plate current to an incremental change in plate voltage, or:

$$\frac{-1}{R_i + R_k} \times \frac{\Delta I_b}{\Delta I_b} = \frac{\Delta I_b}{\Delta E_b} \qquad (22\text{-}5)$$

Any change in plate current may be selected which will provide convenient values of ΔI_b and ΔE_b, and thereby determine a second point on the dc load line. For this example, the increment of I_b selected is 125 ma. Therefore:

$$\frac{\Delta I_b}{\Delta E_b} = \frac{\Delta 125 \text{ ma}}{\Delta 125 \text{ ma}} \times \frac{-1}{600 \text{ ohms}}$$

$$\frac{\Delta I_b}{\Delta E_b} = \frac{\Delta 125 \text{ ma}}{\Delta\, 75 \text{ volts}}$$

On the plate family of curves in Figure 22-4, the X coordinate of the second dc load line point is found by moving to the left of point A - a distance equal to ΔE_b (75 volts). This is labeled point B. From point B, the Y coordinate is found by moving up a distance equal to ΔI_b (125 ma.). This establishes point C. The dc load line is drawn by passing a straight line through points A and C.

To establish the quiescent point (point Q), a cathode bias line must be constructed. To construct the cathode bias line, a point is found on each side of the dc load line which satisfied the condition of bias. To find point D, an arbitrary bias voltage of -20 volts was selected then divided by the value of the cathode resistance, 350 ohms. The resulting value of current, I_{Rk}.

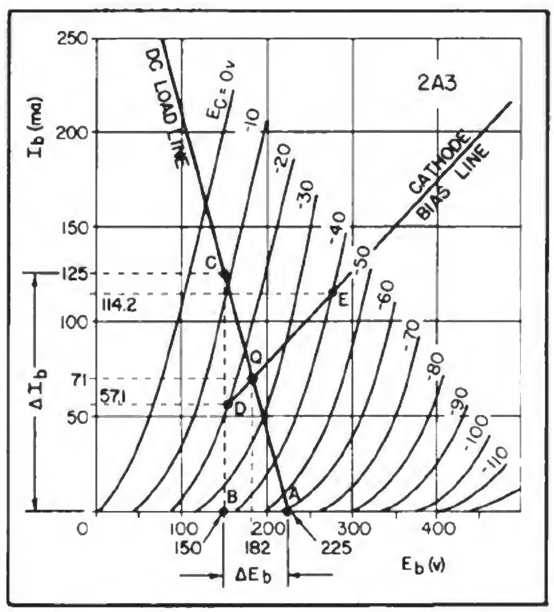

Figure 22-4 - DC load line and cathode bias line.

(which is also I_b) equals 57.1 ma. This positions point D at the coordinates of -20 volts, $I_b = 57.1$

ma. Point E is found in like manner using E_c = -40 volts. The position of point E is E_c = -40, I_b = 114.2 ma. Connecting points D and E forms the cathode bias line.

The intersection of the dc load line and the cathode bias line is the quiescent point (Q point). The quiescent values of voltage and current, as determined from the graph, are E_c = -25 volts, E_b = 182 volts, and I_b = 71 ma. Once the Q point is established, it is used in constructing the ac load line, since this line also passes through the quiescent point.

Q3. What is the point slope method of constructing a load line?

22-5. Constructing the ac Load Line

When switch S_1 in Figure 22-3 is closed, the signal generator varies the grid voltage of the power triode. This places the circuit in a dynamic or ac condition, so that plate current possesses an ac as well as dc component. A changing current in the primary of the output transformer will cause transformer action and the impedance of the load will appear as a reflected impedance in the primary. As a rule, the reflected impedance is much larger than the dc resistance of the primary winding. Therefore, the opposition to the ac component of plate current is different than the opposition to the dc component. For all practical purposes the plate load impedance is considered to be that of the reflected impedance (Z_p). The slope of the ac load line is then equal to $-1/Z_p$.

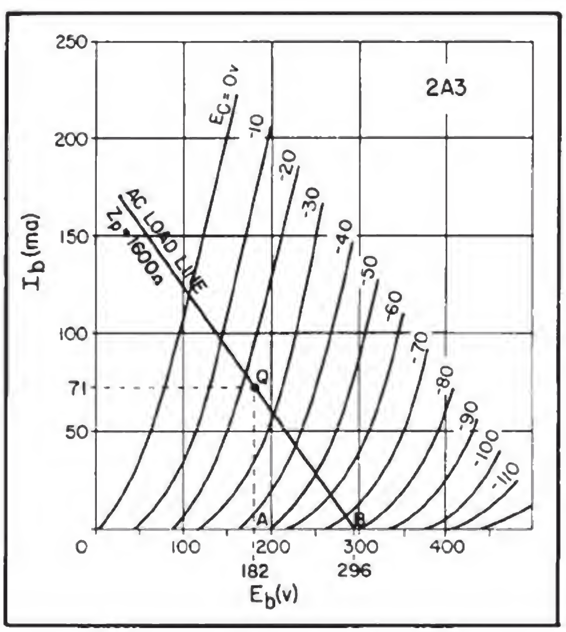

Figure 22-5 - AC load line for 1600 ohm load.

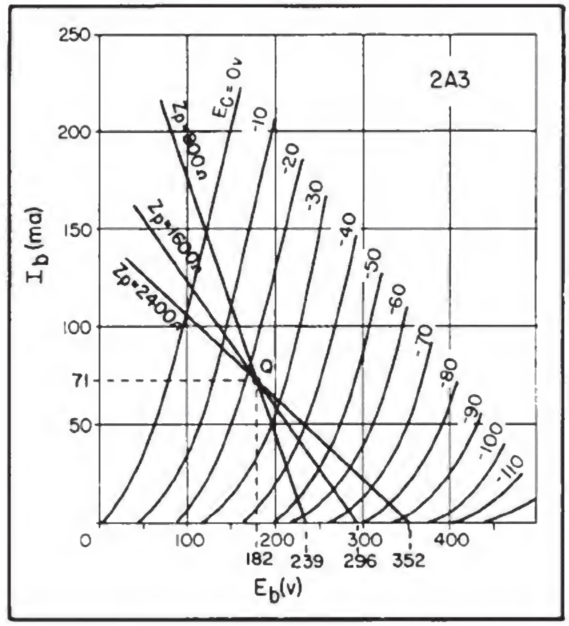

Figure 22-6 - AC load lines for various loads.

To construct the ac load line on the plate family of curves, a point-slope method is used. This method is similar to that used to construct the dc load line except that the known point is now the quiescent point. When the current does not change, the circuit is the same as the quiescent condition. Therefore, the ac load line must contain the Q point. In the circuit under discussion, the Q point was established by the dc load line and the cathode bias line intersecting at E_c = -25 volts, E_b = 182 volts, and I_b = 71 ma. Figure 22-5 shows the Q point positioned on the family of curves and the ac line constructed through it.

Since $-1/Z_p$ is the slope of the ac load line, its value for this circuit is -1/1600. This is converted to a more useable form when multiplying by $\Delta I_b/\Delta I_b$. As was the case for the DC load line, any convenient value of ΔI_b can be selected. If the value of ΔI_b is chosen as 71 ma, the ΔI_b and ΔE_b values become:

$$\frac{\Delta I_b}{\Delta E_b} = \frac{-1}{1600} \times \frac{\Delta 71 \text{ ma}}{\Delta 71 \text{ ma}} = \frac{\Delta -71 \text{ ma}}{\Delta 113.6\text{v}}$$

or approximately:

$$\frac{\Delta\ -71 \text{ ma}}{\Delta\ 114 \text{ v}}$$

The negative sign simply indicates the slope is negative.

A3. A method that provides a means of constructing the dc load line on a graph too small to show the Y-intercept point using the X-intercept point and the slope of the line.

With reference to Figure 22-5, the change in I_b from point Q to point A is 71 ma. while the change in E_b from point A to point B is 114 volts. Therefore, point B has the coordinates of $I_b = 0$, $E_b = 296$ volts.

The ac load line is drawn by passing a straight line through points B and Q, and, for Figure 22-5, represents a reflected impedance of 1600 ohms. Since the ac load line is used to calculate the power output of an amplifier, the slope is of prime importance. Figure 22-6 shows the effect of different reflected impedances upon the slope of the ac load line.

Q4. What would happen to the ac load line slope if the output transformer turns ratio were decreased?

22-6. Voltage, Current, and Power Relationships

The plate current and plate voltage that would result at any grid voltage may be found on the ac load line in Figure 22-7.

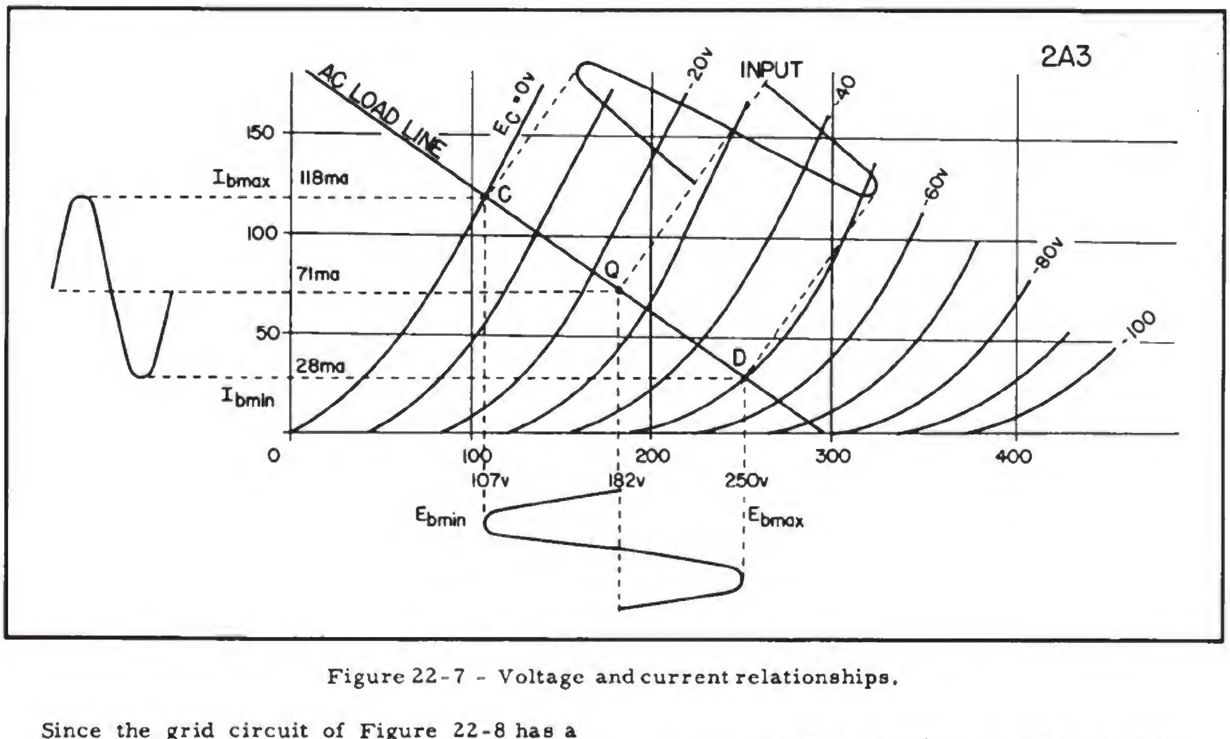

Figure 22-7 - Voltage and current relationships.

Since the grid circuit of Figure 22-8 has a bias of -25 volts provided by the cathode network, the 25 volt peak signal will drive the grid voltage between 0 and -50 volts. Where the ac load line intersects the 0 volt grid line (point C) and the -50 volt grid line (point D) provide the maximum and minimum values of plate current and plate voltage. At point D, e_b is maximum (250 volts) and at point C, e_b is minimum (107 volts). The peak-to-peak plate voltage swing is 143 volts. The plate current, i_b, at point C is maximum (118 ma.), and at point D, i_b is minimum (28 ma.). The peak-to-peak plate current swing is 90 ma.

Since the voltage and current variations in the primary of the transformer are equal in amplitude to the plate voltage and current, the power delivered to the primary may be calculated. If the transformer is 100% efficient, either the primary or secondary power can be considered the output power, since $P_p = P_s$. By knowing the plate voltage and plate current swings, the power of the amplifier may be found in the following manner.

Ac power is equal to E_{rms} times I_{rms}.

$$E_{rms} = \frac{e_b\ max - e_b\ min}{2\sqrt{2}} \qquad (22\text{-}6)$$

$$I_{rms} = \frac{i_b\ max - i_b\ min}{2\sqrt{2}} \qquad (22\text{-}7)$$

$$P_o = \frac{e_b\ max - e_b\ min}{2\sqrt{2}} \times \frac{i_b\ max - i_b\ min}{2\sqrt{2}}$$

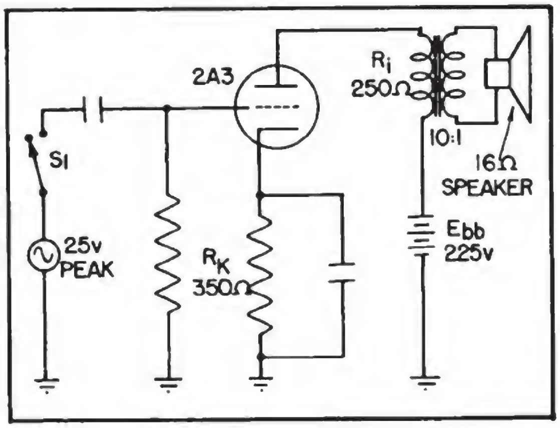

Figure 22-8 - Single-ended power amplifier.

$$P_o = \frac{(e_b \text{ max} - e_b \text{ min}) \quad (i_b \text{ max} - i_b \text{ min})}{8} \qquad (22\text{-}8)$$

The power output for the circuit under discussion is calculated.

$$P_o = \frac{(143 \text{ volts})\ (90 \text{ ma.})}{8} = 1.61 \text{ watts}$$

This 1.61 watts of power will be delivered to the speaker if the output transformer is 100% efficient. This power is supplied by the power supply and not all the power put into the amplifier is useful.

Q5. Calculate P_o if the effective value of plate voltage and current are 200 volts and 100 ma.

22-7. Plate Efficiency

The plate efficiency of a power amplifier is the ratio of the ac power output (P_o) to the dc power input (P_{in}), and is expressed as a percentage. Power input is the product of the average plate current (I_b) and the average plate voltage (E_b). Therefore, the percent of efficiency of an amplifier may be found by the following formula:

$$\text{Efficiency (\%)} = \frac{P_o \text{ (ac)}}{P_{in} \text{ (dc)}} \times 100$$

$$= \frac{P_o}{E_b \times I_b} \times 100 \qquad (22\text{-}9)$$

By calculating the percent of efficiency, one can determine what percent of the dc power supplied to an amplifier stage is converted to usable ac power output. The power supplied to an amplifier that is NOT converted to usable power is dissipated by the tube in the form of heat. This is called PLATE DISSIPATION, and can be calculated by:

$$\text{Plate dissipation} = P_{in} \text{ (dc)} - P_o \text{ (ac)} \qquad (22\text{-}10)$$

For example, the % of efficiency and plate dissipation for the circuit shown in Figure 22-3 can be computed using the ac load line in Figure 22-7.

$$P_{in} = I_b\ E_b = 71 \text{ ma.} \times 182 \text{ volts} = 13 \text{ watts}$$

$$P_o = \frac{(I_b \text{ max} - I_b \text{ min})(E_b \text{ max} - E_b \text{ min})}{8} \qquad (22\text{-}8)$$

$$P_o = \frac{(90 \text{ ma})\ (143 \text{ volts})}{8} = 1.6 \text{ watts}$$

$$\text{Efficiency (\%)} = \frac{1.6 \text{ w}}{13 \text{ w}} \times 100 = 12.4\%$$

$$\text{Plate dissipation} = 13 \text{ w} - 1.6 \text{ w} = 11.4 \text{ w}$$

These calculations show that a class A amplifier is inefficient and that plate dissipation is high. Greater efficiency can be obtained by operating the amplifier class AB or B.

In a class A amplifier with no signal applied, no ac power will be developed; but the average value of plate current and voltage will remain the same. Therefore, the plate dissipation will equal the power input. The no-signal plate dissipation in the above example is 13 watts. The plate dissipation rating of a 2A3 is 15 watts, which is greater than the 13 watts of no-signal plate dissipation calculated. If this were not the case, the grid bias would have to be increased by a sufficient amount so that the actual plate dissipation would not exceed the rating of the tube. This is an important factor since plate dissipation will have an influence on the life of the tube.

Q6. If a tube operates with 15% efficiency, what input power is necessary to provide 6 watts of output power?

22-8. Distortion

Examining the plate current swing in Figure 22-7 reveals that it does not make equal swings above and below the quiescent value. In this example, the peak positive current swing is 47 ma. (118 ma - 71 ma.), and the peak negative swing is 43 ma. (71 ma - 28 ma.). As a result the output signal becomes distorted by the operation of

A4. The slope would increase, since the reflected impedance decreases.

A5. $P_o = \frac{(200\ v)(100\ ma)}{8} = 2.5$ watts

A6. 40 watts.

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the power amplifier. This type of distortion is called AMPLITUDE DISTORTION or HARMONIC DISTORTION, and is caused by the non-linear characteristics of the tube.

Since the positive and negative plate current swings are not equal, the output waveform will differ from the pure sine wave input. The waveforms in the plate circuit can be analyzed by a non-sinusoidal waveform.

Non-sinusoidal waveforms are made up of a dc component and many pure sine waves having different frequencies. The fundamental frequency of the pure sine wave is the frequency of the non-sinusoidal waveform. The frequencies of the other pure sine waves are whole-numbered multiples of the fundamental frequency and are called harmonics. For example, if the frequency of a non-sinusoidal waveform is 1,000 cps, the fundamental frequency is 1,000 cps, the second harmonic frequency is 2,000 cps, the third harmonic frequency is 3,000 cps, etc. The harmonics are broken down into two groups—the even order harmonics (second, fourth, sixth, etc.) and the odd order harmonics (third, fifth, seventh, etc.). The amplitude of the harmonics depend upon the amount of distortion; that is, the deviation of the non-sinusoidal waveform from a pure sine wave.

Distortion of a waveform is analyzed by the amount of each harmonic present. In the output waveform of a single-ended triode amplifier operated calss A, the second harmonic has the greatest amplitude of all the harmonics present. Thus, the second harmonic has the greatest effect upon the output waveform. This is called SECOND HARMONIC DISTORTION. The percent of second harmonic distortion may be calculated by the following formula:

$$\%\ \text{Distortion} = \frac{i_b\ max + i_b\ min - 2I_{bo}}{2\ (i_b\ max - i_b\ min)} \times 100 \quad (22\text{-}11)$$

where: i_b max = Maximum value of instantaneous ac

i_b min = Minimum value of instantaneous ac

I_{bo} = dc component of plate current in quiescent state

The percent of second harmonic distortion for the circuit of Figure 22-3 is:

$$\%\ \text{Distortion} = \frac{118\ ma. + 28\ ma. - 2(71\ ma.) \times 100}{2(118\ ma. - 28\ ma.)}$$

% Distortion = 2.2%

Generally, distortion up to 5% is permissible.

When necessary either of two methods may be used to reduce distortion. The first method is to reduce the input signal and thereby operate the tube over the smaller portion of the non-linear characteristic curve. This action reduces the distortion but also reduces the power output by a large amount. This method is used only in extreme cases.

The second method is to select a value of reflected impedance to position the ac load line so that it passes through the most equally spaced and parallel grid lines of the plate family of curves. With this method, a great reduction of distortion can be obtained with only a small decrease in output power.

Since the reflected impedance affects both distortion and the power out, some rule must be used to provide MAXIMUM UNDISTORTED POWER. The term "undistorted" refers to the 5% or less. It has been determined that for maximum undistorted power output of a triode power amplifier, the plate load should be twice the value of the ac plate resistance ($Z_p = 2r_p$). Using this relationship, the percent of distortion is usually below 5%, and the output power is usually about 90% of what it is when $Z_p = r_p$.

Q7. What causes distortion in a power amplifier?

22-9. Frequency Response

The frequency response of the power amplifier is mainly determined by the output transformer. Figure 22-9 shows the frequency response of a normal power triode amplifier using an output transformer.

This frequency response curve is considered flat between 100 cps and 10k cps. The amplifier is designed to have as flat a response as possible over this mid-frequency range. At the low frequency end of the response curve, the gain falls off due to the inductive reactance of the primary of the transformer. Primary inductive reactance is designated as X_{Lp}.

Since $X_{Lp} = 2\pi f_{Lp}$, lowering f will lower the X_L of the primary winding. X_{Lp} is in parallel with the reflected impedance, and at some frequency, X_{Lp} will be less than 10 Z_p. At this time, the gain of the stage begins to fall off.

At the high frequency end of the response curve, the gain falls off due to the leakage in-

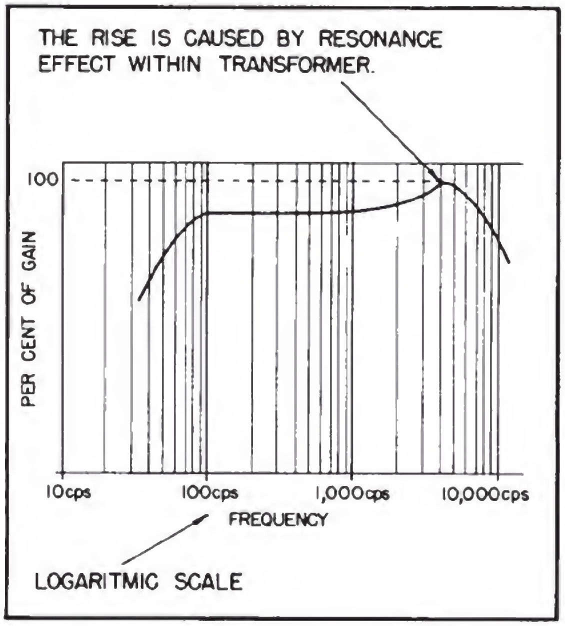

Figure 22-9 - Frequency response curve.

ductance of the transformer and the stray capacitance of the circuit, which includes the capacitance between the windings of the transformer. The leakage flux, the flux that does not link primary and secondary turns, will increase at higher frequencies. This lack of linkage between primary and secondary, and the shunting effect of the stray capacitance in the primary and secondary of the transformer, causes the gain to fall off at the higher frequencies.

Because a dc component of current flows through the primary winding of the transformer in a single-ended power amplifier, the primary inductance is not constant. A graph of the effective inductance of the primary (called INCREMENTAL INDUCTANCE) versus the dc current flow through the primary winding is shown in Figure 22-10. Notice the large decrease in the incremental inductance when the core of the transformer becomes saturated. This incremental inductance must be used to calculate the primary inductive reactance X_{Lp}. Since the incremental inductance is smaller than the inductance without dc current, X_{Lp} will be smaller and the low frequency response will be reduced.

To increase the low frequency response of the amplifier, the transformer core material is made with large cross-sectional areas or the dc current through the primary is effectively eliminated by the use of push-pull circuitry. To increase the high frequency response, the transformer leakage flux and the stray capacitance are reduced by better transformer design. For this reason, a good high fidelity audio system contains expensive, high-quality output transformers.

Q8. How does the dc component flowing through the output transformer primary affect frequency response?

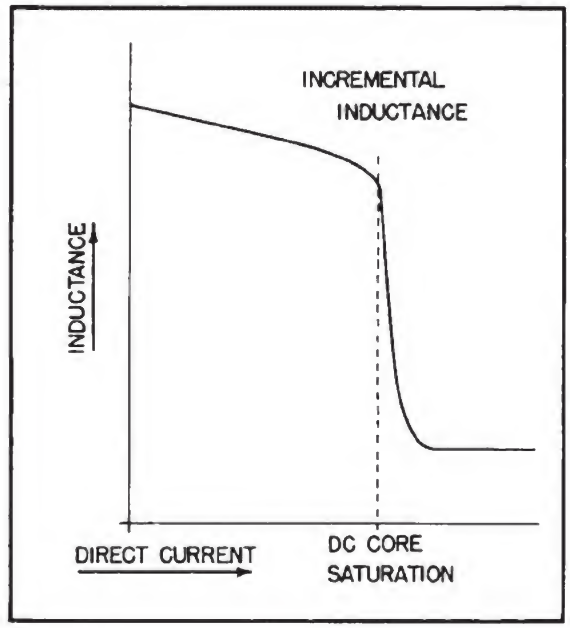

Figure 22-10 - Incremental inductance.

22-10. Beam Power Tubes

POWER SENSITIVITY is another term used with power amplifiers. It is the ratio of the power output in watts to the grid signal voltage causing it (when no grid current flows). If grid current flows, the term usually means the ratio of plate power output to grid power input. Pentodes and beam power tubes require less driving power than triodes for the same power output and thus have a greater power sensitivity.

Power amplifier circuits normally use vacuum tubes which are specifically designed for purposes of power amplification. One such tube is the beam power tube. Its special design gives it the ability to handle very high values of current. The plate characteristics of the beam power tube are similar to the characteristics of a pentode tube. The primary difference between these two tubes is that in the beam power tube the electrons are concentrated into sheets as they are attracted to the plate. The sheets or beams of electrons are formed by a set of beam-forming plates located inside the tube.

A7. The non-linear characteristics of the tube.

A8. An increase in the dc flowing through the primary winding causes primary inductance and reactance to decrease, thereby affecting the low frequency response of the amplifier.

The location and configuration of all the elements of a beam power tube are shown in Figure 22-11. The cathode is large and flat on two sides to provide a large emitting surface. The plate is usually corregated to increase the effective plate area, thereby increasing its power dissipation capability.

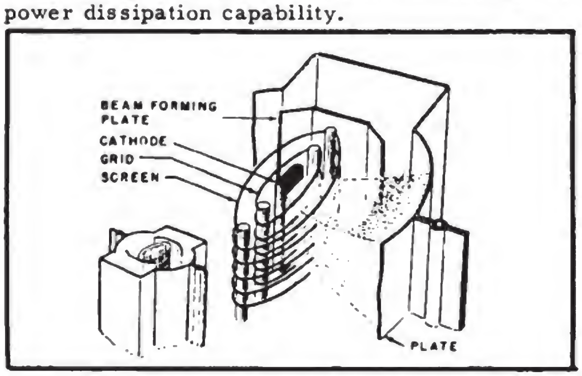

Figure 22-11 - Beam power tube.

Another basic difference in the construction of the beam power tube is the way in which the grids are wound. In the beam power tube, the screen grid is wound directly in line with the control grid, which reduces the likelihood of electrons striking the screen grid on their way to the plate. Figure 22-12A shows how the control grid and screen grid wires in an ordinary tetrode determine the electron paths. The wires are out of alignment, so that many of the electrons which pass through the control grid wires are deflected from their paths, striking the screen grid. This produces a screen current which reduces the value of the plate current. The need for a very large plate current in power tubes makes this characteristic undesirable.

In Figure 22-12B, the screen grid wires are wound directly in line with the control grid wires so that the screen grid is shaded from the electron stream. As a result, the screen grid intercepts fewer electrons. This result of a lower value of screen grid current in the "shadow" of the control grid is called SHADING The overall result of the addition of the beam-forming plates, the shading of the grids, and the use of a corrogated plate is a tube which can handle a substantial amount of electrical power without a great deal of distortion. The plate and control grid of the beam power tube are electrically isolated, the plate current is high, and the plate resistance is relatively low.

Another important function of the beam-forming plates is the suppression of secondary electrons from the plate. Figure 22-13 shows how the electrons pass through the control grid and screen grids, past the ends of the beam-forming plates, and finally to the plate. Since the beam-forming plates are connected to the cathode, they are at the same potential as the cathode; that is, highly negative with respect to the plate. Because of this, the beam-forming plates produce and effect equivalent to a space charge in the area between the screen and the plate. This area of effect, shown in Figure

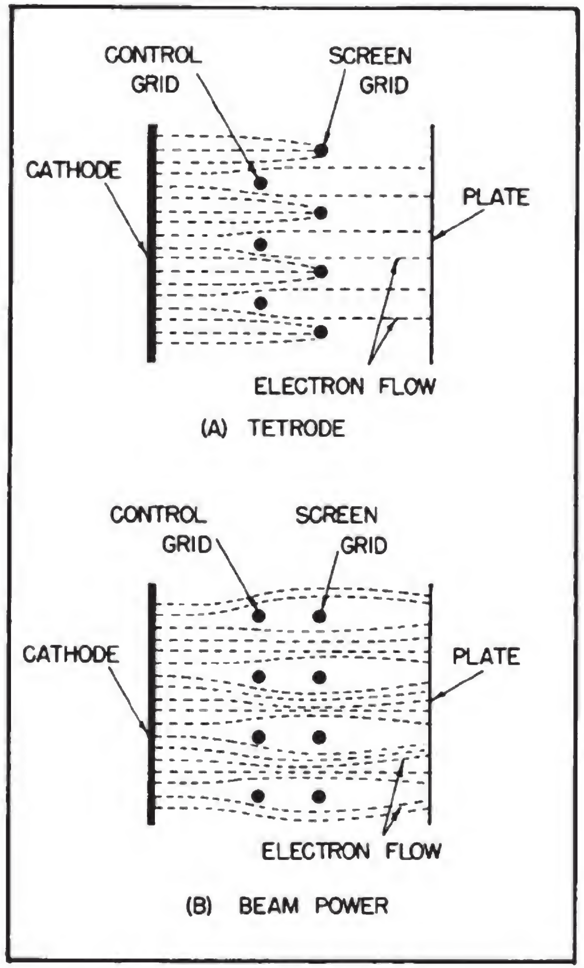

Figure 22-12 - Comparison of beam power and tetrode tubes.

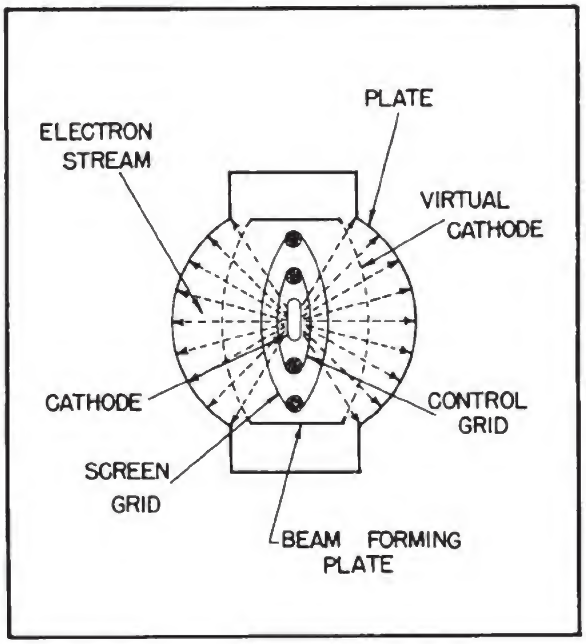

Figure 22-13 - Top view of beam power tube.

22-13 as dashed lines joining the ends of the beam forming plates, is identified as the VIRTUAL CATHODE. Its effect is to repel secondary electrons emitted from the plate, preventing them from reaching the screen grid.

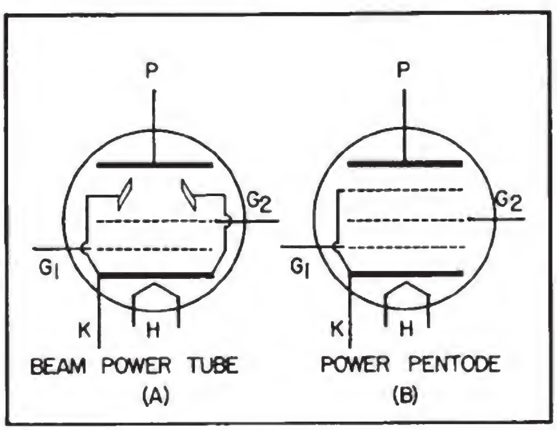

Figure 22-14 - Schematic representation of the beam-power tube and the power pentode.

In some tubes, the effect of the virtual cathode is achieved by the use of a suppression grid in place of the beam-forming plates. The results are identical in both versions.

Figure 22-14A symbolizes the beam power tube with the beam-forming plates, whereas, Figure 22-14B shows the version in which a grid replaces the beam forming plates. As can be seen, there is no difference between the schematic representation of the power pentode and the schematic symbol used to represent the ordinary pentode.

The plate characteristic curve for the beam power tube differs from that of the ordinary pentode as shown in Figure 22-15. Notice the rapid rise in plate current for the beam power tube as shown by the solid line. The more gradual rise in plate current for the normal pentode shown by the dashed line is an important detail relative to powerhandling ability with minimum distortion. The solid-line curve shows that the zone in which the plate current is primarily a function of the plate voltage is much more limited; the plate current becomes substantially independent of plate voltage at a much lower value of plate potential. This characteristic enables the beam power tube to handle greater amounts of electrical power at lower values of plate voltage than the ordinary pentode. In addition, the beam power tube produces less distortion than the ordinary pentode while accommodating a larger grid swing and plate current change.

A typical beam power tube is the 6V6. The family of characteristic curves for the 6V6 is shown in Figure 22-16.

A 2,000 ohm load line may be plotted on the family of curves. If it is assumed that E_{bb} is 400 volts, I_b is 200 ma. and the bias is -5 volts, then the Q point will intersect the -5 volt bias line where plate current is approximately 83 ma. and the plate voltage is approximately 230 volts.

Using the curves in Figure 22-16, two tube parameters will be computed—the transconductance and the plate resistance. The amplification factor will not be computed because its value is not a serious consideration when discussing power amplifier operation.

The transconductance for the 6V6 beam power tube may be computed using the family of curves and the following formula:

$$gm = \frac{\Delta i_b}{\Delta e_c} \ (e_b,\ e_{c_2}\ \text{constant}) \qquad (19\text{-}7)$$

Holding the plate voltage constant at a value of 230 volts and allowing the grid voltage to swing five volts above and below the -5 volts bias line, plate current will swing from approximately 55 ma. to 114 ma.—a change of 59 ma. Substituting the value found from the curves, the transconductance of the 6V6 is 5900 micromhos.

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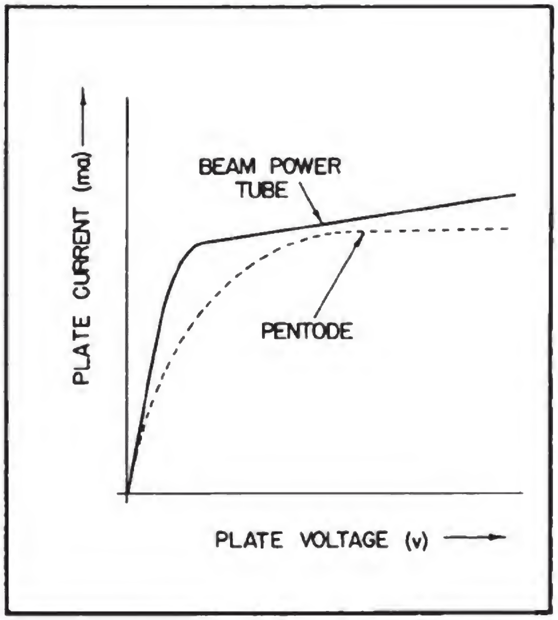

Figure 22-15 - Characteristic curve of a beam power tube as compared to the curve for an ordinary pentode.

This transconductance is higher than the 4100 micromhos given in the tube manuals. The discrepancy is due primarily to the use of values differing from those suggested by the tube manual.

The computations of the plate resistance (r_p) of the 6V6 beam power tube will be accomplished in the same manner as it was in the other tube types. The equation is:

$$r_p = \frac{\Delta e_b}{\Delta i_b} \quad (e_c,\ e_{c2} \text{ constant}) \qquad (19\text{-}6)$$

If the bias voltage is maintained at a constant -5 volts, and if a change of plate voltage is arbitrarily taken from 225 to 250 volts, the plate current will change from approximately 82.6 to 83.2 ma.—a change of 0.6 ma. Substituting these values into the plate resistance formula, the value of the plate resistance is approximately 41,000 ohms.

Q9. What is the purpose of a load line when used with the beam power tube?

Q10. What is the most apparent advantage of the beam power tube as compared to the conventional tetrode?

Q11. What features of the beam power tube give it greater current handling capability?

22-11. Beam Power Audio Amplifier

The circuit configuration of the audio amplifier using a beam power tube is much the same as the triode power amplifier circuit. The exception is the inclusion of a screen bypass capacitor, a screen voltage, and a screen dropping resistor. This circuit is shown in Figure 22-17.

The voltage and component values necessary to plot a load line for the circuit in Figure 22-17 are shown in the diagram. These values are suggested by the tube manual. The conventional

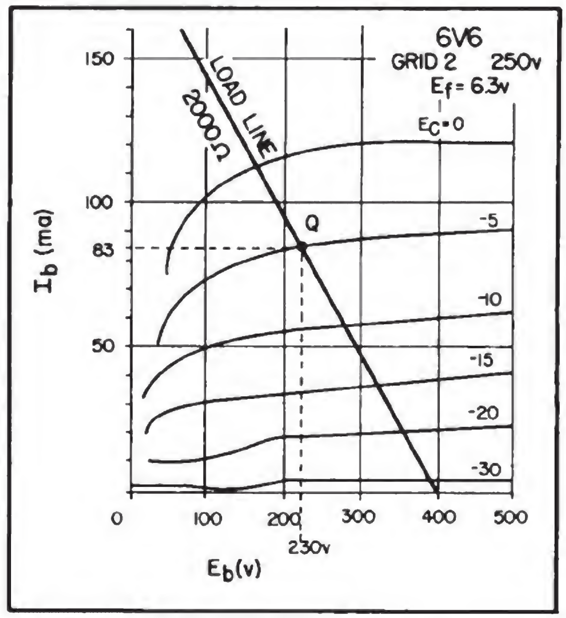

Figure 22-16 - Family of curves for a 6V6 beam power tube with a 2K load line.

method of plotting a load line by first finding the cathode bias line cannot be used with the beam power tube because of the parallel nature of the grid bias lines. To establish the operating point, the quiescent values of current and voltage are taken from the tube manual and are transferred to the characteristic curves in Figure 22-18. Having established the operating point, the dc load line with a slope of -1/500 is passed through this point. It has a slope equal to the reciprocal of the reflected impedance. The value of reflected impedance is given as 5,000 ohms. Therefore, the slope will be -1/5,000. The established bias voltage is -12.5 volts. The tube will be driven by a 25 volt signal. This means that the grid voltage with respect to

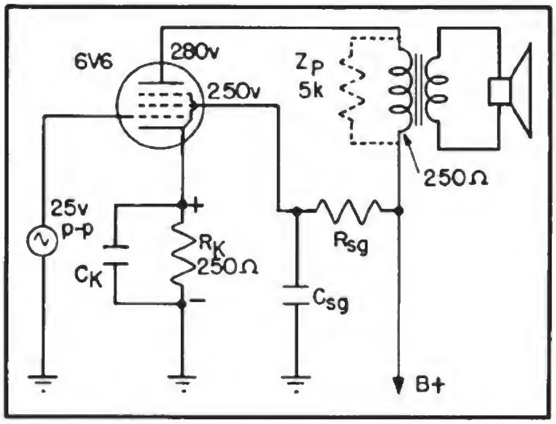

Figure 22-17 - Beam power amplifier.

ground will be zero volts at the peak of the positive alternation, and a minus 25 volts at the peak negative alternation. Point A on the ac load line represents the maximum positive voltage swing, and point B represents the maximum negative voltage swing. The maximum and minimum values are found in the ordinary fashion, and they are:

i_b max = 82.5 ma, e_b max = 438 v, i_b min = 13 ma, e_b min = 26 v, i_{bo} = 45 ma, e_{bo} = 250 v.

From these current and voltage values, the percentage of distortion, power output, and plate efficiency may be computed. This is done in much the same way as for the triode amplifier. However, the formulas used to compute these values for the beam power tube power amplifier are slightly different from those of the triode. The derivation of these new formulas requires an analysis of considerable length. For this reason, only the values of second harmonic distortion and power output which can be found through the use of the previous formulas will be used. The purpose of this is to compare the advantages of the beam power audio amplifier to the triode type. The percentage of second harmonic distortion for the circuit in Figure 22-17 is 3.76%. This is not the total amount of distortion present, only the percentage of second harmonic distortion. The value of second harmonic distortion of the triode power amplifier in Figure 22-3 is 2.2%. The beam power type produces slightly more distortion.

The power output from the 2A3 circuit in Figure 22-3 is 1.61 watts. The power output for the 6V6 circuit is 3.94 watts, almost twice as much output power as the 2A3 triode. This comparison is more striking when the input voltages are compared. The input voltage to the 2A3 was 50 volts peak-to-peak. Using the 6V6 beam power tube with half as much input voltage, the power output is nearly double that of the 2A3 triode.

The plate resistance of the 6V6 is 50,000 ohms. It seems reasonable that the value of reflected impedance should also be 50,000 ohms. Such is not the case. Generally, the reflected impedance is one-tenth the ohmic value of the plate resistance. If a load line for a value of reflected impedance near the value of the plate resistance were plotted, it would appear practically flat on the characteristic curves. The value of the reflected impedance is controlled by the turns ratio of the output transformer.

Q12. What is the primary advantage of the beam power amplifier as compared to its triode counterpart?

Q13. What controls the frequency response of the beam power audio amplifier?

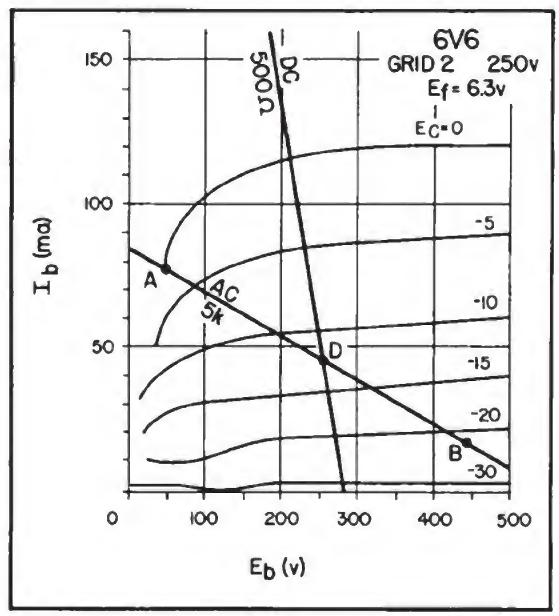

Figure 22-18 - Load lines.

PUSH-PULL POWER AMPLIFIER

It was previously shown that the beam power tube was capable of providing a power output greater in magnitude than its triode tube counterpart under the same operating conditions. It

A9. To give an approximate idea of the plate voltage and plate current that may be expected with a given load and a specified grid voltage.

A10. It has the ability to pass a greater value of current when a high voltage is applied to its grid.

A11. The beam forming plates, and the shading of the screen grid from the control grid.

A12. Greater power output with less voltage input.

A13. The same factors that controlled the response of the triode audio amplifier—the output transformer.

will now be shown that the PUSH-PULL POWER AMPLIFIER will provide a greater power output with less distortion than a single-ended power amplifier under the same operating conditions. The schematic diagram of the push-pull amplifier is shown in Figure 22-19.

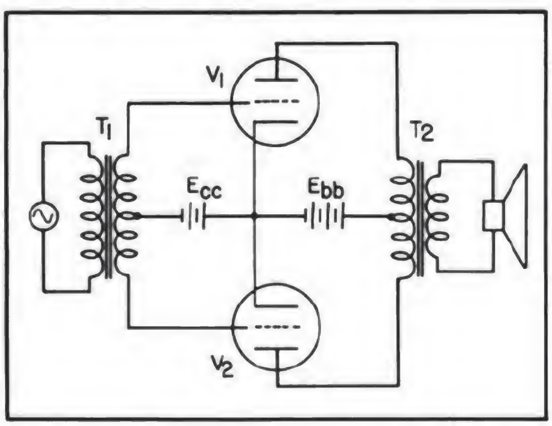

Figure 22-19 - Push-pull power amplifier.

The requirements for a push-pull power amplifier are as follows: It must have two input signals of equal amplitude, and of opposite polarity. The center-tapped secondary of the input transformer, T_1, will provide these necessary requirements. The circuit must also be balanced so that the signals will be amplified equally. Balancing will be considered in detail later in this chapter.

22-12. DC Flow

The path of the quiescent plate current through V_1, in Figure 22-19, will be analyzed beginning at the cathode connection. Current flows from cathode to plate of V_1, down through the top half of the output transformer primary, through the power supply and back to the cathode. The current path of V_2, starting at the cathode connection, flows from cathode to plate of V_2, up through the bottom half of the output transformer primary, through the power supply and back to the cathode.

The two tubes used in Figure 22-19 are the same type and are tested to insure that their conduction characteristics are nearly the same. When two tubes of the same type possess the same conduction characteristics, they are said to be MATCHED.

The two tubes are matched, have equal plate loads connected to a common power supply, and have the same bias voltage. Therefore, the quiescent plate currents through V_1 and V_2 are equal.

Since equal plate current flow through each half of the primary in opposite directions, the resulting magnetic fields are equal in intensity but are opposing each other. Thus, the magnetizing effect of the direct currents on the iron core is cancelled and there can be no dc core saturation of the output transformer.

Bias for the push-pull amplifier may be provided by a battery (fixed bias) or, as shown in Figure 22-20, by a common cathode resistor (cathode bias). By using either arrangement equal bias is obtained for each tube.

Q14. Would an air core transformer be used as the output transformer for an audio power amplifier? Explain.

22-13. AC Flow

The circuit shown in Figure 22-21 is a push-pull amplifier which is biased so that the operation is class A. This means that current will flow through each tube for 360 degrees of the input signal. The signals applied to the tubes will have the instantaneous polarities shown; that is, the grid of V_1 is positive with respect to the center tap at the instant the grid of V_2 is negative with respect to the center tap. Plate current increases through V_1 (i_{b1}) and decreases through V_2 (i_{b2}). The proportion of increase and decrease through each tube is equal. Assume

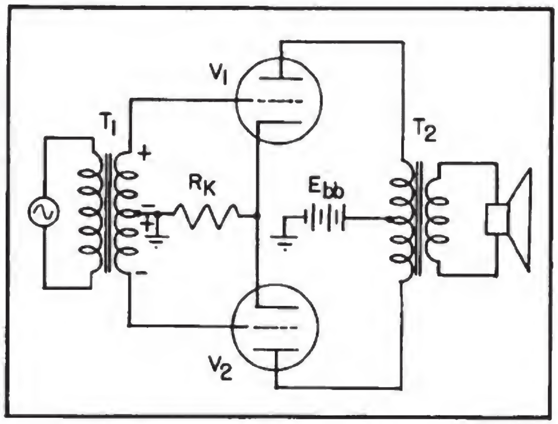

Figure 22-20 - Push-pull amplifier (cathode bias).

that i_{b1} flowing through the top half of the primary produces a counterclockwise field. Then i_{b2} flowing up through the lower half of the primary will produce a clockwise field. This is so because the entire primary is wound in the same direction, but the current flows in opposite directions through each half. Thus, if an expanding counterclockwise field induces a positive voltage in the secondary (caused by an increase in i_{b1}), the collapsing clockwise field caused by the decreasing i_{b2} will also induce a positive voltage. This will occur for one-half cycle of the inputs with conditions reversing during the other half cycle. This makes the outputs of the two tubes additive at all times. It should be noted that if both fields expand or collapse equally at the same time, there would be no voltage induced in the secondary. This explains the necessity of two input signals of opposite polarity.

22-14. Cancellation of Second Harmonics

Second harmonics are eliminated in the push-pull output, as shown in Figure 22-22. The dynamic i_b-e_c curve for the tube V_2 is inverted with respect to that of V_1 to show the phase relationship between the output signal components of the two tubes. (The outputs shown, are as they appear across the secondary.) Thus, when the grid voltage of V_1 swings positive, the grid voltage of V_2 is going in the negative direction. Plate current of V_1 increases as plate current of V_2 decreases. The plate current swing about the X-X axis for tube V_1 is not symmetrical because the tube is operating on a non-linear portion of the i_b-e_c characteristic curve. The same condition is true of the plate current swing about the X'-X' axis of V_2.

The plate current curves of each tube may be resolved into a fundamental and second harmonic. Thus, the axis of the fundamental and its second harmonic is displaced from the axis of the original plate current curve by an amount equal to the peak value of the second harmonic. Combining the fundamental components of both tubes gives an output of twice the amplitude of one tube. However, when the second harmonics are combined, the resultant is zero because they are 180 degrees out of phase. The fundamental output current has the same waveform as the input voltage; the same as what would have been produced, had both tubes been free of second harmonics.

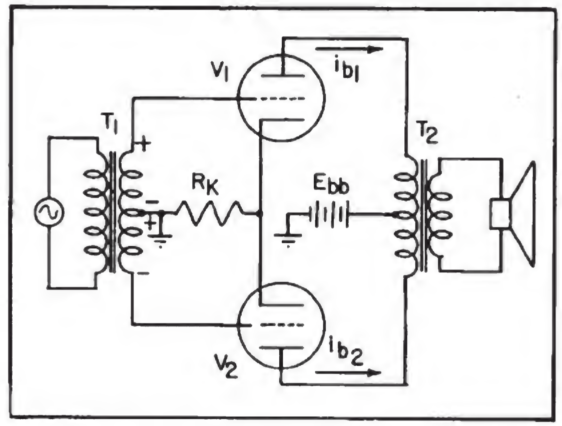

Figure 22-21 - Push-pull amplifier with signal applied.

Q15. What is one advantage of the push-pull amplifier as compared to the single-ended power amplifier?

Q16. Would the plate efficiency for the push-pull power amplifier (Figure 22-21) be a high or low value? Explain.

22-15. Balancing Networks

As mentioned previously, matched tubes are used in push-pull amplifier circuits to insure equal values of current and voltage in the output. No matter how well matched two tubes may be, there will be some differences in their characteristics, thus producing unequal outputs. The center tap on the transformer is critical to the output. If the tap is not physically located in the exact center of the winding there will be unequal outputs from the tubes. Therefore, a

A14. No. The permeability of the transformer core would have to be much greater than that of air.

A15. The elimination of even-order harmonic distortion.

A16. It would be a comparatively low value because the tubes are operated class A.

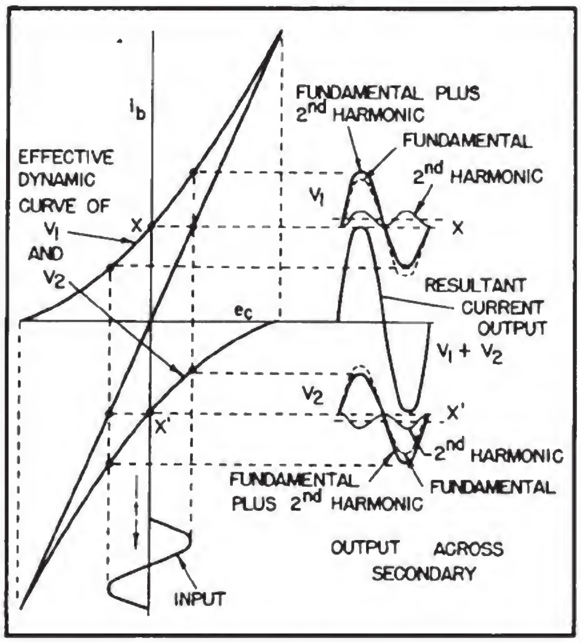

Figure 22-22 - Second harmonic elimination.

means to insure that the outputs of the tubes are the same is desired. This is provided by the use of BALANCING NETWORKS.

When the direct component of the plate current through each tube is not equal, a cathode balancing network, such as the one shown in Figure 22-23, may be used to make the direct currents equal through the two tubes. By adjusting the potentiometer arm of R_3, the value of the grid-to-cathode voltage (bias) to each tube may be changed. In this way, the tube currents may be adjusted exactly equal to each other. This adjustment is usually made while observing accurate ammeter measuring the individual plate currents. The network shown in Figure 22-24 is another method of balancing, called GRID BALANCING.

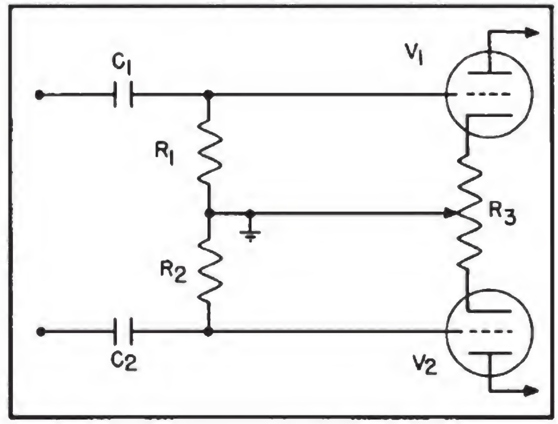

Figure 22-23 - Cathode balancing.

The purpose of this balancing network is to insure that the outputs of both tubes are equal. This network is necessary because no matter how well two tubes are matched, they will not possess exactly the same parameters.

By changing the position of the wiper arm of potentiometer R_1, the magnitude of the input signals to the tubes may be varied to cause equal outputs. For example, if V_1 has a slightly greater transconductance than V_2, the potentiometer arm would be moved towards the top to decrease the magnitude of the input to V_1, and at the same time increase the size of the input to V_2. This adjustment is made by observing the voltage waveform across the cathode resistor, R_2, on an oscilloscope. When the circuits are balanced the current increase through V_1 is equal to the decrease in current through V_2 and vice-versa. Thus, the current through the cathode resistor is constant, developing only a dc voltage equal to that at qui-

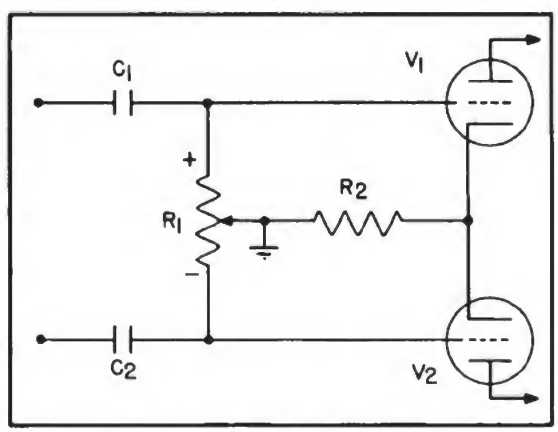

Figure 22-24 - Grid balancing.

escence across R_2. Therefore, the circuits are balanced when a minimum signal appears across the cathode resistor R_2.

22-16. Comparison of Single-Ended and Push-Pull Amplifiers

Some of the advantages of using the push-pull amplifier instead of the single-ended amplifier have been mentioned. There are no effects due to core saturation in the push-pull amplifier because of the balanced direct currents flowing in the primary of the transformer. It was also shown that the push-pull amplifier eliminated even-order harmonic distortion by the process of cancellation. One other advantage of the push-pull amplifier is that there is no hum in the output caused by the power supply ripple. In a single-ended power amplifier driving a loudspeaker, the power supply ripple will cause the plate current to increase and decrease at the ripple frequency, causing a hum to be heard in the output speaker. This will not occur in a push-pull stage, since an increase in power supply voltage will cause an increased plate current through both tubes with equal and opposite fields resulting about the transformer primary, and the effects will cancel. The same will occur when the power supply decreases. Providing the push-pull stage is balanced, no voltage will be induced in the secondary due to the power supply ripple.

Another advantage of a push-pull stage is that a decoupling network is not necessary, providing the circuit is properly balanced. The purpose of the decoupling network, as discussed in Chapter 19, is to prevent the plate current variations from causing the output of the power supply to vary at this ac rate. The reason this network is not necessary in a push-pull stage is because the input signals are of opposite polarity causing one tube current to increase while the other tube current decreases. Thus, the current through the power supply is constant and a varying voltage is not developed across it. For this same reason, a cathode bypass capacitor is not required when using a common cathode resistor.

Q17. What are the advantages of the push-pull amplifier as compared to the single-ended amplifier?

Q18. What condition must exist to allow all of the advantages of the push-pull amplifier to be operative?

Q19. What are the two types of balancing?

22-17. Classes of Operation

The push-pull power amplifier may be operated calss A, AB or B. The class of operation used thus far has been class A. Class A operation is used where plate efficiency is not essential. Class AB operation exists when the tube conducts more than 180 degrees but less than 360 degrees of the input cycle. It is used when class B operation causes great distortion due to the non-linearity of the characteristic curves near plate current cut off. Class B operation is used when high efficiency from an audio amplifier is desired. When class B oper-

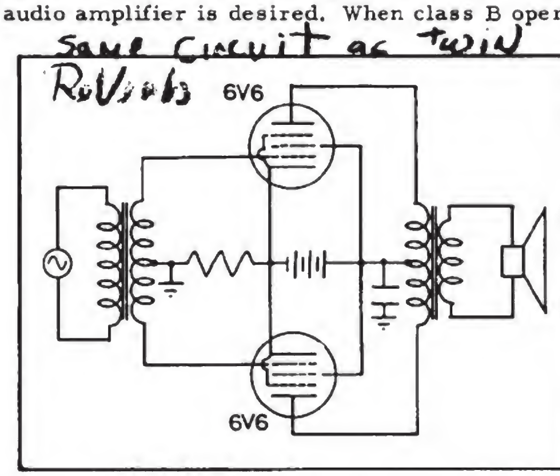

Figure 22-25 - Beam power push-pull amplifier.

ation is used, each tube only conducts for 180° of the input cycle. Class C operation is never used with an audio amplifier of any type because of the high degree of distortion it produces.

22-18. 6V6 Push-Pull Power Amplifier

The diagram in Figure 22-25 shows a push-pull amplifier using beam power tubes. The circuit is the same as that of the triode push-pull circuit except that provisions are made for the screen grid voltages. The screen grid voltage is usually the same as the plate voltage.

Referring to a manufacturer's tube manual, a comparison between the 6V6 class A single-ended and the 6V6 class A push-pull amplifiers can be made. With a plate voltage of 250 volts, the single-ended power output is about 4.5 watts. For the same plate voltage, the push-pull power output is about 10 watts. This larger output power is a result of using a larger input signal which is possible with push-pull operation.

A17. The push-pull amplifier is not subject to distortion caused by core saturation; all even-order harmonic effects are eliminated; power supply hum is eliminated or reduced; and there is no need for a decoupling network.

A18. The tubes must be balanced.

A19. Cathode and grid balancing.

EXERCISE 22

1. What is a voltage amplifier?
2. What is an audio power amplifier?
3. What is the difference between an audio voltage amplifier and an audio power amplifier?
4. What is a beam power tube?
5. What characteristics of the beam power tube gives it its high current-handling capacity?
6. What is the function of the beam forming plates?
7. What is meant by the term "shading?"
8. What is the purpose of shading?
9. What is a virtual cathode?
10. What does a virtual cathode do? Is it desirable or undesirable?
11. Describe the difference between the plate family of characteristic curves for the normal pentode, and the beam power tube?
12. How do the tube parameters for a beam power tube compare with those of the other types of tubes?
13. Compare the characteristics and parameters of the 6V6 and the 6SN7.
14. What is the purpose of a load line on a triode plate characteristic curves?
15. What information may be obtained from a load line?
16. What is meant by the term "dynamic transfer characteristics?"
17. If the load resistance of a triode amplifier is increased, what happens to its power out, gain, and its transfer of power?
18. What is the single-ended power amplifier?
19. What is an output transformer?
20. Give a definition of a power amplifier?
21. Of what value is an equivalent circuit?
22. What is reflected impedance?
23. Why is impedance matching necessary?
24. How can a value of reflected impedance be found?
25. What is the relationship of the impedance ratio to the turns ratio?
26. What is the relationship between power in the primary of a transformer to the power in the secondary?
27. What is the difference between the voltage amplifier and the power amplifier?
28. How is the dc load line for a triode with a transformer in the plate circuit computed?
29. Why does the plate voltage exceed the supply voltage with the transformer load?
30. What is amplitude distortion?
31. What is second harmonic distortion?
32. What is the relationship between second harmonic distortion and amplitude distortion?
33. What is a harmonic?
34. What is meant by the term "fundamental frequency?"
35. What happens to the percentage of distortion when the value of the reflected impedance is caused to increase?
36. What happens to the output power of a power amplifier when the reflected impedance is increased past the point of maximum transfer of power? Explain.
37. How is the power input to a power amplifier computed?
38. What is incremental inductance?
39. What does incremental inductance have an effect on?
40. How may the high frequency response of a power amplifier be increased?
41. What is the primary difference between a power amplifier using a triode tube and one using a tube such as the 6V6?
42. For a given power output, which tube requires the greater signal input—the 2A3 or the 6V6?
43. What is a push-pull amplifier?
44. What is meant by the term "balance" in connection with the push-pull amplifier?
45. What is core saturation? Does the term apply to a push-pull amplifier? Explain.
46. Explain the operation of a class A push-pull amplifier?
47. What are the advantages of a push-pull amplifier as compared to the single-ended amplifier using the same type of tube?
48. How may balancing be accomplished?
49. If efficiency were not considered, what class of operation would be best suited for an audio amplifier?
50. Compare the push-pull 6V6 operated class B to the single-ended 6V6 operated class A.

CHAPTER 23

DECIBELS, MICROPHONES, AND SPEAKERS

To understand what decibels are, it is first necessary to establish a need for this new system of measurement. This will be accomplished through the use of an analogy and an everyday application.

What is meant by the term "quiet"? A simple answer, of course, it is the absence of noise. But, just how much noise or the lack of it constitutes a perfect quiet? The terms "quiet" and "noisy" are obviously related. The very nature of the words indicates the possibility of various levels of quiet and noise. The expressions noisy, very noisy, and extremely noisy receive wide and frequent use in our modern mechanized society. The terms quiet and very quiet do not enjoy great popularity, but also indicate a difference in the noise level.

At night in the country, the air may be filled with the sound of many crickets. If only one cricket breaks a silence, and begins emitting its characteristic sound, the sound in reference to the previously still night is quite loud. When another cricket blends in, there is a perceptible change in the volume of the noise. As the number of chirping crickets increases, the human ear cannot determine how many crickets are making the increased noise. If several hundred crickets were to sound off in a densely populated city during that city's rush hour, the sound of the crickets would go unnoticed because it would be lost in the high level noise of traffic. The noise of the crickets would add little to the total noise level. Therefore, the human ear can perceive an increment of noise change about a low level, but can not detect the same interval of change about a higher level.

The high fidelity amplifier is also an example of the human ear's response to changes in sound intensity. If an amplifier were operated at a power output of 10 watts, the power output would have to be increased by 25%, to a value of 12.5 watts, before the ear would perceive a change in volume. If another increase in volume is desired, the power output would have to be increased an additional 25%, to a value of approximately 15.6 watts.

From these examples it can be seen that the human ear has a non-linear response to sound energy. The human ear, in fact, is a logarithmic sensing organ, and for that reason, noise levels must be measured by a logarithmic system of measurement. The unit chosen to express values of noise intensity is the BEL or its subunit the DECIBEL. The name of this unit is given to commemorate the early work in telephony performed by Alexander Graham Bell. One decibel, which is one-tenth of a bel, is the smallest unit of acoustical power change that the human ear can discern.

23-1. The Decibel

The bel or decibel is a means of expressing acoustical power ratios. Its use can be incorporated to include electrical power ratios so that the gain or loss of a system may be expressed in units of decibels. However, the decibel is only applicable to electrical systems which have the primary function of signal handling. It is not used with electro-mechanical devices such as motors and solenoids. The formula used to determine the numerical value of the bel is given as follows:

$$\text{bel} = \log_{10}\left(\frac{P2}{P1}\right) \qquad (23\text{-}1)$$

Since the decibel is one-tenth of a bel:

$$\text{decibel} = \text{db} = 10 \log_{10}\left(\frac{P2}{P1}\right) \qquad (23\text{-}2)$$

where: P_1 = power input in watts
P_2 = power output in watts

Because the base of the logarithms used in this section is (10), the base will be omitted from all of the logarithmic formulas to follow. If the base is changed it will be so specified. Whenever a base for a logarithm is not shown it may be assumed to be ten.

Often-times, the output and input power is not known, and many times it is not convenient to determine. However, if the input and output current, voltage and impedance are known; the basic decibel equation may be modified to render a new equation.

Since:

$$P_1 = \frac{(E_1)^2}{R_1} \quad \text{and} \quad P_2 = \frac{(E_2)^2}{R_2}$$

substituting: $$db = 10 \log \frac{\frac{(E_2)^2}{R_2}}{\frac{(E_1)^2}{R_1}}$$

dividing: $$db = 10 \log \frac{(E_2)^2 R_1}{(E_1)^2 R_2}$$

The product $(\frac{E_2}{E_1})^2 \times \frac{R_1}{R_2}$ may be multiplied using the law of logarithms that states that the factors of a product may be multiplied by adding their logarithms.

therefore: $$db = 10 \left[\log (\frac{E_2}{E_1})^2 + \log \frac{R_1}{R_2}\right]$$

The exponent in the expression $(E_2/E_1)^2$ may be removed by employing another law of logarithms which states that to raise a number to a power the logarithm of that number may be multiplied by the exponent. Then, the expression $\log (E_2/E_1)^2$ becomes:

$$2 \log \frac{E_2}{E_1}$$

Substituting and expanding:

$$db = 20 \log E_2/E_1 + 10 \log R_1/R_2$$

To simplify the equation, the expression $10 \log R_1/R_2$ is rewritten so that the numerical coefficient 10 is changed to 20. This is done to facilitate a recombination of the equation. This operation is accomplished in the following manner:

$$10 \log R_1/R_2$$

for convenience, let:

$$X = R_1/R_2$$

Then the expression will read:

$$10 \log X$$

The power that the factor (X) is raised to is always assumed to be one. If that power is written as $\frac{2}{2}$ instead of $\frac{1}{1}$:

or: $$10 \log X^{\frac{2}{2}}$$

Using the laws of logarithms:

$$20 \log X^{\frac{1}{2}}$$

Re-substituting R_1/R_2 for X:

$$20 \log (R_1/R_2)^{\frac{1}{2}}$$

or: $$20 \log \sqrt{R_1/R_2}$$

then: $$db = 20 \log E_2/E_1 + 20 \log \sqrt{R_1/R_2}$$

Expressing this logarithmic sum as an algebraic product, a simplified formula in terms of voltage and resistance may be found.

$$db = 20 \text{ Log} \left[(E_2/E_1)\sqrt{R_1/R_2}\right] \qquad (23\text{-}3)$$

If the output impedance is equal to the input impedance, the equation is:

$$db = 20 \log \frac{E_2}{E_1} \qquad (23\text{-}4)$$

The same operation may be performed to determine the nature of the equation in terms of current and resistance.

Since: $P_1 = (I_1)^2 R_1$ and $P_2 = (I_2)^2 R_2$

Then: $$db = 10 \log \frac{(I_2)^2 R_2}{(I_1)^2 R_1}$$

By the same method as equation 23-3:

$$db = 20 \log \left[(I_2/I_1)\sqrt{R_2/R_1}\right] \qquad (23\text{-}5)$$

If the input impedance is the same as the output impedance:

$$db = 20 \log I_2/I_1 \qquad (23\text{-}6)$$

With these relationships, the gain of a stage of amplification can easily be expressed in decibels.

23-2. Application of Decibels

To properly apply decibels, a review of the operations made with logarithms is helpful. For a review of the properties and rules of operation for logarithms, refer to Volume 8.

The following are several examples of the application of logarithms to electrical problems:

1. How many decibels correspond to a power ratio of 100?

$$db = 10 \log \frac{P_2}{P_1}$$

$$db = 10 \log 100$$

$$db = 10 \times 2 = 20 \text{ db}$$

2. How many decibels correspond to a voltage ratio of 100 (assume equal resistances)?

$$db = 20 \log \frac{E_2}{E_1}$$

$$db = 20 \log 100$$

$$db = 20 \times 2 = 40 \text{ db}$$

3. If an amplifier has a gain of 20 db, what power ratio does this gain represent?

$$\frac{P_2}{P_1} = X$$

$$db = 10 \log X$$

$$20 = 10 \log X$$

$$\log X = 2$$

$$X = 100$$

4. If an amplifier has a 30 db gain, what voltage ratio does this gain represent (assume equal resistances)?

$$\frac{E_2}{E_1} = X$$

$$db = 20 \log X$$

$$30 = 20 \log X$$

$$\log X = 1.5$$

$$X = 31.6$$

The voltage ratio is 31.6 to 1.

5. A certain microphone rated at -75 db (a minus sign represents a loss) is connected to a preamplifier through an attenuator rated at -10 db. The final audio amplifier has a gain of 30 db, and is driven by the preamplifier. What must the db gain of the preamplifier be to balance the losses in the microphone and attenuator? (All db gains and losses have the same reference level).
The total loss is 75 plus 10 or 85 db, and therefore, the preamplifier must have a gain of 85 db to bring the losses to zero db. From this point the main amplifier increases the gain 30 db above the common, or zero, reference level.

6. If the input to a certain loudspeaker is increased from 5,000 milliwatts to 6,000 milliwatts, could the volume change be detected by the human ear?

$$db = 10 \log \frac{P_2}{P_1}$$

$$db = 10 \log \frac{6,000}{5,000}$$

$$db = 10 \log 1.2$$

$$db = 10 \times 0.0792$$

$$db = 0.792$$

No. Because a change of one db is barely discernible, a change of 0.792 would not be detected.

7. If a one volt signal is applied across the 600 ohm input impedance of an amplifier, and 500 volts is developed across the 5,000 ohm output impedance, what is the db power gain?

$$P_2 = \frac{E_{out}^2}{R_{out}} = \frac{500^2}{5,000} = 50 \text{ watts}$$

$$P_1 = \frac{E_{in}^2}{R_{in}} = \frac{1}{600} = 0.00166 \text{ watt}$$

$$db = 10 \log \frac{P_2}{P_1}$$

$$db = 10 \log \frac{50}{0.00166}$$

$$db = 10 \log 30,000$$

$$db = 10 \times 4.4770$$

$$db = 44.8$$

8. If the noise level in a certain transmission line is 50 db down from the desired signal level of 10 mw, how much power is contained in the noise level?

$$db = 10 \log \frac{P_2}{P_1}$$

Where P_1 is the power in milliwatts contained in the noise level, and P_2 is the power in milli-

watts contained in the desired signal level.

Substituting: $50 = 10 \log \frac{10}{P_1}$

$$5 = \log \frac{10}{P_1}$$

$$10^5 = \frac{10}{P_1}$$

$$P_1 = \frac{10}{10^5} = 10^{-4} = 0.0001 \text{ mw}$$

Q1. Would a perceptible change in volume occur if the power output of an amplifier is increased from fifteen to nineteen watts? Why?

Q2. What is indicated by a plus sign preceding a db value?

23-3. Reference Levels

Considerable confusion has resulted from the use of various so-called zero-power reference levels. The term "zero reference level" is in itself somewhat confusing because it does not mean that the power is zero. It does mean that the output level is referred to an arbitrary level designated as the reference, or zero level; and as such it is perhaps one of the most convenient ways of expressing a power ratio. It is meaningless to say, for example, that a certain amplifier has an output of 30 db unless reference is made to some established power level.

It is common practice in naval and other telephone work to consider 6 milliwatts as the reference power level. Other values are also used in this and other fields; for example 1, 6, 10, and 12.5 milliwatts, depending upon which unit is most convenient under the circumstances.

The voltage gain or loss of a microphone, a transmission line, or a voltage amplifier is also expressed in decibels. In general, transmission lines introduce a loss, and voltage amplifiers introduce a gain.

The voltage output of a microphone may be expressed in terms of decibels below one volt per dyne per cm^2. In other words, one dyne acting on one square centimeter and producing an output of one volt is taken as the zero-decibel output level.

When the voltage gain of an amplifier stage is given in decibels the input and output impedances must be assumed to be equal unless otherwise specified.

When a certain arbitrary power reference is used, the db gain or loss is given a special designation. One of these designations is the dbm, the power level in decibels referred to one milliwatt, as:

$$\text{dbm} = 10 \log \frac{P_2}{1 \times 10^{-3}} \qquad (23\text{-}6)$$

Where P_2 is the output power in watts.

As an example of the use of the dbm unit, if an amplifier has a power output of 1445 milliwatts, what is its gain in dbm?

$$\text{dbm} = 10 \log \frac{P_2}{1 \times 10^{-3}}$$

$$\text{dbm} = 10 \log \frac{1445 \times 10^{-3}}{1 \times 10^{-3}}$$

$$\text{dbm} = 10 \log 1445$$

$$\log 1445 = 3.1599$$

$$\text{dbm} = 10\ (3.1599)$$

$$\text{dbm} = 31.6$$

The value of 31.6 dbm may be checked by the following means:

$$31.6 = 10 \log \frac{P_2}{1 \times 10^{-3}}$$

Dividing by 10:

$$3.16 = \log \frac{P_2}{1 \times 10^{-3}}$$

Taking the antilog of both sides:

$$1445 = \frac{P_2}{1 \times 10^{-3}}$$

$$P_2 = 1445 \text{ milliwatts}$$

The volume level of an electrical signal made up of speech, music, or other complex tones is measured by a specially calibrated voltmeter called a VOLUME INDICATOR. The volume levels registered on this indicator are expressed in volume units (VU). The number of units is numerically equal to the number of decibels above or below the reference level. Zero VU represents a power of one milliwatt dissipated by an arbitrary load resistance of 600 ohms at 1000 ~ (corresponding to a voltage of 0.7746 volts). Thus when the VU meter is connected to a 600 ohm load, VU readings in decibels can be used as a direct measure of power above or below a one milliwatt reference level.

Q3. Why must a reference level be specified?

MICROPHONES

23-4. Nature of Sound

Many people are startled when they speak for the first time to a person whose image or voice they have previously seen or heard reproduced electrically or mechanically. They are often prompted to remark that the person looks or sounds so much different in real life. The difference in sound or appearance is due to the lack of fidelity of the electrical equipment involved. For example, at a radio station sound energy is converted into electrical energy by the use of a microphone. This electrical energy is then amplified and transmitted. It may then be received by a radio receiver which converts the received signal into a form which is then applied to a loudspeaker. The function of the loudspeaker is to convert the electrical energy into sound energy. It is by this last process that the original sound is reproduced. The faithfulness of the reproduction is dependent upon the type and quality of the components used to develop, transmit, receive, and reproduce the signal.

If either the microphone used to initially transform the sound energy into electrical energy, the transmitter used to amplify and transmit the signal, the receiver used to detect and amplify the signal, or the loudspeaker used to change the electrical energy to sound energy have a poor frequency response, the output will be distorted. Distortion is realized when the output signal is not the same as the original signal. It is unlikely that a device will ever be constructed that will perfectly reproduce the human voice.

An examination of the nature of sound, and the devices used to reproduce it will make evident the reasons for the imperfections in fidelity.

The origin of a sound is always a vibrating body. A good example of a vibrating body which produces a sound is a tuning fork. When a tuning fork such as the one shown in Figure 23-1 is struck, the TINES begin to vibrate. When the tine marked A moves to the right, it pushes the molecules in that region to the right thereby producing a COMPRESSION of air molecules. When the same tine moves to the left, it produces an area of reduced pressure called a RAREFACTION. Every sound wave is composed of these compressions and rarefactions of air. If the tines are permitted to vibrate continuously, a continuous sound would be generated. The frequency of the sound produced by the tuning fork is dependent upon the length and mass of the tines. The longer they are, the lower will be the frequency of the sound produced.

When the compressions and rarefactions of air produced by the tuning fork reach the eardrum of the listener, they produce small inward and outward motions of the eardrum. The process of hearing the sound is thus begun. The velocity at which the sound waves travel is dependent upon the medium through which they travel. If the medium is air, the velocity of sound is given at approximately 1080 feet per second. The response of the human ear to sound frequencies is given as from twenty to twenty thousand cycles per second. However, it is an especially good ear that can discern sound frequencies as high as eighteen thousand cycles per second.

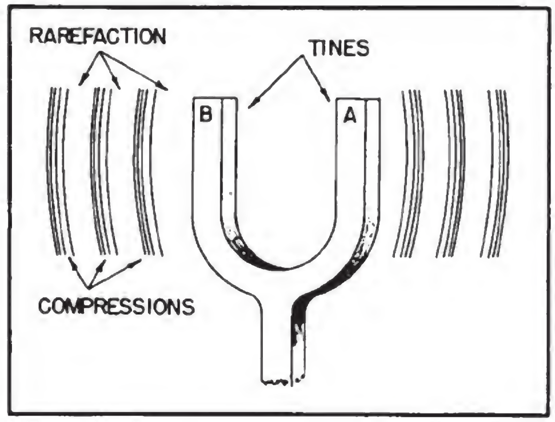

Figure 23-1 - Tuning fork.

The sound produced by the tuning fork is composed of many frequencies. There is the normal vibrating frequency which is called the FUNDAMENTAL FREQUENCY, and other frequencies which are called OVERTONES. In musical instruments, the overtones are usually multiples of the fundamental. These multiples are also called HARMONICS.

A sound may be described as having three characteristics: PITCH, LOUDNESS and QUALITY. The pitch of a sound generally depends on the frequency of the fundamental. As the frequency increases, the pitch also increases.

Loudness describes the magnitude of the auditory sensation produced by the sound. The sound may be so loud as to produce physical pain.

Quality is a comparison of different notes. A note is defined as a tone of a definite pitch. The pitch or note can be played on a guitar and a trumpet, and the listener will be able to distinguish between them. The reason for this is that both the guitar and the trumpet produce a note that is not only composed of the fundamental frequency, but also includes the harmonics. When the two notes differ in quality, they also differ in the harmonic frequencies produced and the relative intensity of their

A1. To the trained ear the change would be noticeable because the gain is slightly greater than one db.

A2. It means that the system in question is capable of producing a gain.

A3. Because more than one value may be used as the reference level.

---

various overtones.

A microphone is used to convert sound energy to electrical energy. When one speaks into a microphone, the audio pressure causes a diaphragm to move in accordance with the pressure applied to it. The diaphragm is attached to a device that causes current to flow in proportion to the instantaneous pressure applied to the diaphragm.

Most microphones are relatively inefficient. That is, the output of electrical energy is considerably less than the input of acoustical energy. Some, however, are more efficient than others; or have a better frequency response. The characteristics of microphones, therefore, will be discussed before the various types of microphones are considered.

Microphones are rated according to their frequency response, impedance, and their sensitivity. For good quality, the electrical waves from the microphone must correspond closely to the magnitude and frequency of the sound waves that cause them, so that no new frequencies are introduced. The frequency range of the microphone (that range of frequencies over which the microphone is capable of responding) need be no wider than the desired over-all response limits of the system with which it is to be used. The microphone response should be uniform, or flat, within its frequency range; and free from any sharp peaks or dips.

Crystal microphones have impedances of several hundred thousand ohms; whereas dynamic microphones have low impedances in the range of from twenty to six hundred ohms. The impedance of a microphone is usually measured between its terminals when some arbitrary frequency in the useful audio range is used.

The actual impedance of a microphone is of importance chiefly as it is related to the load impedance into which the microphone will operate. If the load has a high impedance, the microphone should also have a high impedance, and vice versa. Of course, impedance matching devices may be used between the microphone and its load.

The sensitivity or efficiency of a microphone is usually expressed in terms of the electrical power level which the microphone delivers to a terminating load (the impedance of which is equal to the rated impedance of the microphone) compared to the acoustical energy that is being picked up. Because sound energy at the input is being compared with electrical energy at the output, some basis of comparison must be established.

One method is to assume that a microphone has a sensitivity of 0 db (the level of comparison) if a force of one dyne per square centimeter on the diaphragm produces an output of one volt. The usual method, however, is to assume that the 0 db level represents an input of one dyne per square centimeter and an output of one milliwatt. If it is further assumed that the one milliwatt is developed across an impedance of 600 ohms, then dbm or volume units (VU) may be used. Suppose a microphone is rated at -80 db. This rating means that the energy output is much less than the energy input. Actually, the output is 10^{-8} milliwatt for an equivalent input of one milliwatt, and this is equivalent to -80 db. This rating may be demonstrated by the following equation:

$$\text{db} = 10 \log \frac{P_2}{P_1}$$

$$\text{db} = 10 \log \frac{10^{-8}}{1} = -80 \text{ db}$$

It is important to have the microphone sensitivity as high as possible. High sensitivity means a high electrical power output level for a given input sound level. High microphone output levels require less gain in amplifiers used with them and thus provide a greater margin over thermal noise, amplifier hum, and noise pick-up in the line between the microphone and the amplifier.

The types of microphones available make use of the properties of resistance, inductance, and capacitance. Microphones which make use of the piezoelectric effect are also available. The types of microphones that will specifically be discussed in this chapter are the carbon microphone, the moving coil or dynamic microphone, the velocity microphone, and the crystal microphone. The function of any of these microphones may be graphically shown in Figure 23-2.

23-5. Carbon Microphone

If a piece of pure carbon were split up and made granular, the resulting pile of carbon would possess a value of specific resistance; and would pass a current if the pile were enclosed in a cup. If a variable pressure is applied to the pile its density would change. The contact between the carbon granules would also change.

With an increased pressure, there would be an increase in the number of individual carbon granules that would make contact with each other. Under a reduced pressure, this contact would be diminished. Each tiny air space between granules is effectively an insulator. The combined effect of these small insulators is to produce a pile that possesses varying values of resistance under the influence of a varying pressure. If the source of the pressure variations is the human voice, the compressions and rarefactions of air applied to the carbon pile will also cause its resistance to vary. In fact,

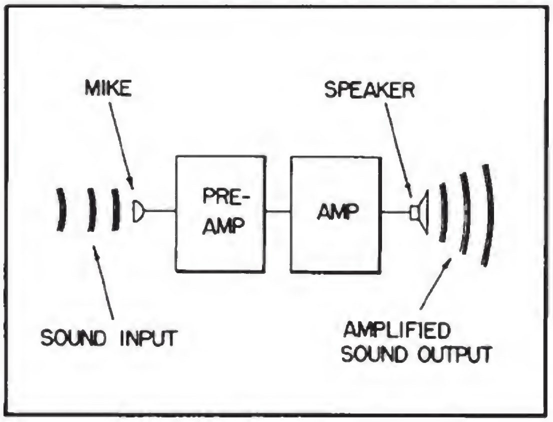

Figure 23-2 - Block diagram of an audio system.

under these conditions, the resistance of the pile will vary at an audio rate. If the carbon pile is compressed, the space between each carbon granule is reduced. If the pressure is reduced, the carbon pile would return to its original density. When pressure is applied, the density of the pile increases; and the resistance of it decreases. When the pressure is released, the resistance of the pile increases. The variable resistance characteristics of the carbon pile is the underlying principle on which the operation of the CARBON MICROPHONE is based. The basic construction of the carbon microphone is as shown in Figure 23-3.

In the single button type of carbon microphone, the carbon granules are placed in a cup or "button", and are permitted to make contact with the suspended perpendicular element which is the DIAPHRAGM. If a stress is placed on the diaphragm, the pressure exerted on the carbon granules is increased; and the resistance of the carbon pile decreases.

In the double-button microphone, there is more of a push-pull action. Any movement of the diaphragm increases the pressure in one cup while decreasing the pressure in the other cup by approximately the same amount. The word approximately is used here because it is highly unlikely that the two cups could be filled with exactly the same amount of carbon granules.

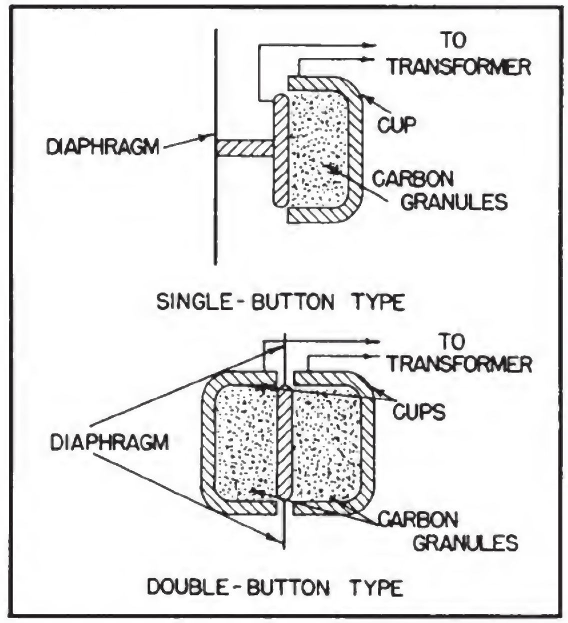

Figure 23-3 - Construction of a carbon microphone.

In the circuit shown in Figure 23-4A, the microphone button is placed in series with a dc battery. Any current flowing in the microphone circuit will also flow through the primary of the transformer. With no movement of the diaphragm, there will be no change in the resistance of the cup. Under these conditions, the direct current flowing through the cup will be constant; and the resulting magnetic field about the primary of the transformer will not fluctuate. There will be no voltage induced in the secondary of the transformer.

When the diaphragm is compressed the resistance of the cup would decrease and the current flow through the circuit would increase. The field that was stationary about the primary will now expand and cut the secondary windings. A voltage will now be induced in the secondary of the transformer. If the pressure on the diaphragm is reduced, the resistance of the carbon pile increases, and circuit current decreases. The voltage induced in the secondary of the transformer will now reverse polarity. If the diaphragm is moved at an audio rate, the voltage induced in the secondary of the transformer will also vary at an audio rate. Therefore, the amount of voltage induced in the secondary is dependent upon the pressure applied to the microphone diaphragm. The frequency of the output voltage is dependent upon the frequency of the input. The frequency limi-

tations of the microphone is governed by the ability of the carbon granules to change their density.

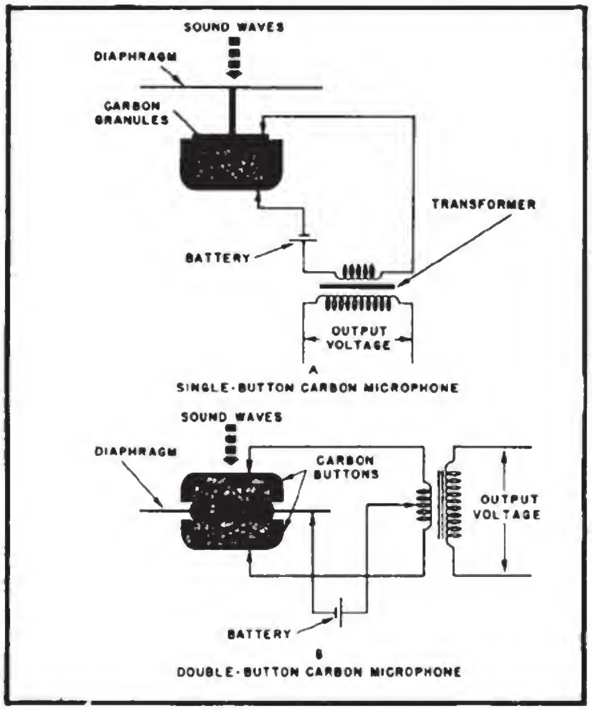

Figure 23-4. Carbon microphone circuit

When the double-button microphone is used, (Figure 23-4B) the amount of possible distortion realized through the constant shuffling of the carbon granules is reduced. The push-pull effect realized by the use of the double button microphone and the center tapped transformer, tends to cancel the even order harmonics.

The term "resonance" also has an application in the audio frequency microphone discussion. The best way to analyze the idea of mechanical resonance is to re-examine the operation of the tuning fork. If two tuning forks of the same frequency were placed close together each of them possessing the capability of vibration, when one of them is caused to vibrate at its fundamental frequency, the other would begin to vibrate. It would do so without physically being touched. The sound waves produced by the vibrating tines will cause the other to vibrate at the same frequency. When this condition occurs, the two forks are said to be in resonance. Resonance is also applied to the metal diaphragm of a microphone because there is a possibility of there being a frequency applied to the microphone that is the natural resonant frequency of the diaphragm. The amplitude of the mechanical vibration at the resonant frequency of the diaphragm is much higher than the vibration at other applied frequencies. If the mechanical resonance occurs within the audio range of the microphone, its output will "peak" sharply everytime the resonant frequency of the diaphragm is applied. This peaking effect at resonance will cause the response of the microphone to be non-linear, and it is therefore disadvantageous. To eliminate its effects, the diaphragm is stretched so that its resonant frequency is higher than the normal voice frequencies applied. Normal voice frequencies are those between the range of approximately 100 to 5,000 cycles per second. The diaphragm is stretched until its mechanical resonant frequency is approximately 6,000 cycles per second. By doing this the response of the microphone is made more uniform over its operating range. The operating range of a carbon microphone is approximately 100 to 5,000 cycles per second.

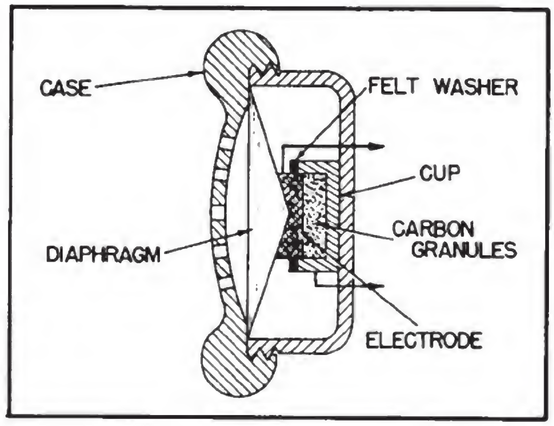

Figure 23-5 - Cross section of the carbon microphone.

The felt washers in Figure 23-5 are provided to furnish DAMPING. The low frequencies applied to the microphone are usually the most intense. The tendency of the diaphragm to maintain the low frequency vibrations after the force is removed is very great. By using the felt washers the vibrations after the force has been removed are minimized or DAMPED.

It will be seen that the carbon microphone possesses certain advantages that make it a valuable device. In comparison to the other types of microphones that will be discussed, the carbon microphone produces a relatively large output. It also has the advantage of being light weight, inexpensive, portable and rugged. It is used in applications where wide frequency response may be sacrificed for good sensitivity. In voice communications, the quality of the speech is not critical. Therefore, the carbon microphone enjoys wide popularity in Naval eletronics.

Because of the low impedance of the carbon microphone, an impedance matching transform-

er is required when it is desired to send the output of the microphone to the high impedance input of a speech amplifier. However, since the output is in the order of about -50 db; the amplification required for the carbon microphone is less than that required by other types of microphones. One disadvantage apparent with the use of the carbon microphone is the noise generated by the loosely packed carbon granules. One other disadvantage of the carbon microphone is that it does require an external dc source.

Q4. What limits the response of the carbon microphone?

Q5. What would happen if the impedance of the carbon microphone were not matched to the impedance of the speech amplifier?

23-6. Dynamic Microphones

A type of microphone that uses the principles and properties of inductance is the MOVING COIL MICROPHONE. The operation of this dynamic microphone is described using the diagram in Figure 23-6. This microphone is given the name dynamic because it has a moving part. The coil winding that is wound around the pole piece is able to move up and down the pole. It is attached to the flexible diaphragm and is caused to move by sound waves striking the diaphragm. As it moves, it passes through the magnetic field set up between the poles of the magnet. Since the diaphragm will move at an audio rate, the voltage induced into the coil when it moves will also vary at an audio rate. The diagram in Figure 23-7 shows a cross section of the moving coil microphone.

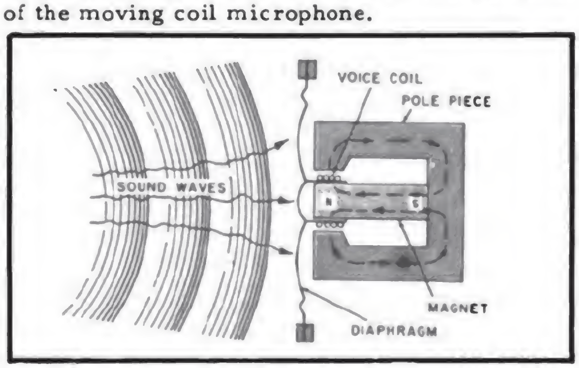

Figure 23-6 - Moving coil microphone

In the diagram shown in Figure 23-7, the diaphragm is located close to the pole piece. The diaphragm is held in place by the ring and washer. The area under the diaphragm is completely enclosed except for the narrow slit designated as S_1. This slit serves to control the response of the microphone by imposing a load on the diaphragm as a result of the increased air resistance of the enclosed air spaces designated as O_1 and O_2. The cavity marked C improves the damping action and the frequency response. It also serves to increase the faithfulness of signal conversion. At the low frequencies, the stiffness of the diaphragm governs its motion and results in a response that normally decreases as frequency applied decreases. The decreased frequency response begins at about 200 cycles and if left uncorrected the sensitivity of the microphone would fall off rapidly below 200 cycles. However, if the effective force on the diaphragm is increased at a rate corresponding to the decrease of motion because of stiffness, a uniform response is obtained.

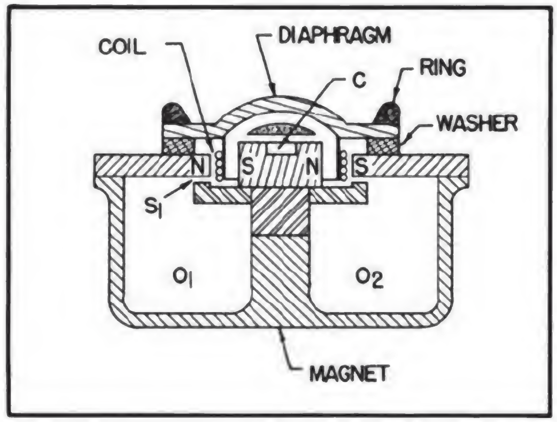

Figure 23-7 - Cross section of the moving coil microphone.

In the moving coil microphone, the uniform response is obtained with an air passage provided by the tube which connects the diaphragm to the air chamber within the magnet. By proportioning the length and diameter of this tube, it is possible to reduce the internal pressure at the desired frequency. Therefore, at low frequencies, the effective force on the diaphragm increases to offset the increased stiffness.

The moving coil microphone is a low impedance device. The variable impedance is given as between 50 and 100 ohms. With this type of microphone, an impedance matching transformer is used. The moving coil microphone can be designed so that its frequency response is from about 30 to 18,000 cycles per second. It has an output in the order of about -85 db. The sensitivity of the moving coil microphone is high. It is light, rugged, moisture proof, small and not subject to the effects of temperature and humidity. It does not require an external source of dc voltage.

Q6. If low cost were the primary consideration, would the carbon or dynamic type be preferred? Why?

A4. The movement of the carbon granules. They must be able to move faster at higher frequencies.

A5. There would not be a maximum transfer of power from the microphone to the amplifier.

A6. The carbon type would probably cost less since it contains fewer and les complicated parts. It has good sensitivity, and provides a higher output than the dynamic mike.

23-7. Velocity Microphones

One of the disadvantages of all microphones discussed thus far has been their undesirable ability to pick up noises emanating from all directions. This disadvantage is overcome through the use of the VELOCITY MICROPHONE. The operation of the velocity mike is fundamentally the same as that of the moving coil mike. Instead of the moving coil, a strip of metal is caused to vibrate in the magnetic field. This type of microphone is shown in Figure 23-8. No diaphragm is shown in the cross section diagram in Figure 23-8. This is because the metal strip called the RIBBON, performs the function of the diaphragm. The metal strip is arranged in such a way so that its length is perpendicular to, and its width is in the plane of the magnetic lines of force. Notice that the pole pieces are constructed in such a way so that air may pass freely through the microphone.

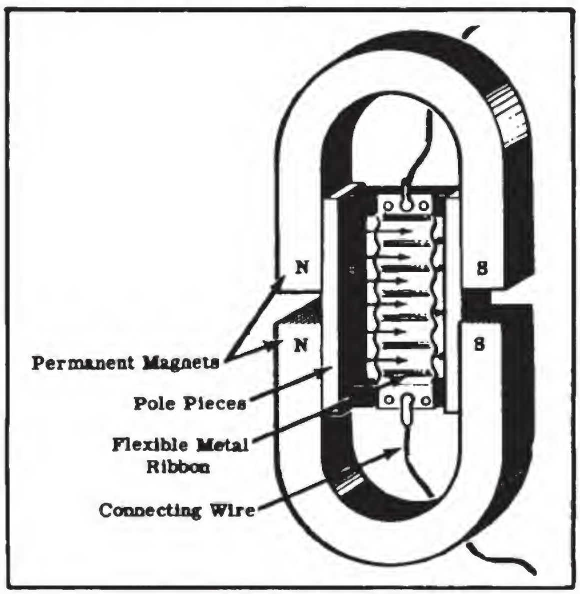

Figure 23-8 - Velocity microphone cross section.

When sound waves strike the ribbon, the vibrations thus established cause the ribbon to pass through the magnetic field. This movement of the ribbon in the field will cause a voltage to be induced in the ribbon which is proportional to the strength of the magnetic field, the velocity at which the ribbon cuts through the field, and the length of the ribbon in the field. Since the ribbon is caused to move through the field at an audio rate, the voltage induced in the ribbon will also vary at an audio rate.

The thin ribbon is subject to strong winds when it is used out of doors. It is for this reason that the microphone is covered both inside and outside with fine silk mesh. This mesh combined with the metal enclosing screen which covers the assembly helps protect it from sudden gusts of wind and the introduction inside the case of any magnetic material.

The name "velocity microphone" is given to this unit because the thin ribbon has a low value of inertia and will respond directly to any changes in air pressure. Since the ribbon can respond to changes in pressure from either the front or back of the microphone equally well, the velocity microphone is a bi-directional mike.

Because the ribbon is delicately balanced between the ribbon supports, the frequency response of the instrument is quite good. The frequency response of the velocity mike is from 20 to 15,000 cycles per second. Since the ribbon is very delicate, the person using this type of mike should stand back from the unit a good eighteen inches. The instrument is sensitive enough to pick up sounds at considerable distances. The output impedance is extremely low, but it can be raised to between 20 and 600 ohms by use of a transformer. The output is approximately -90 db.

Q7. Compare the response of the velocity mike to the response of the carbon mike.

23-8. Crystal Microphones

When pressure is applied to certain crystals, a voltage is generated by the crystal. This effect is known as the PIEZOELECTRIC EFFECT. The CRYSTAL MICROPHONE uses this effect. There are two types of crystal mikes.

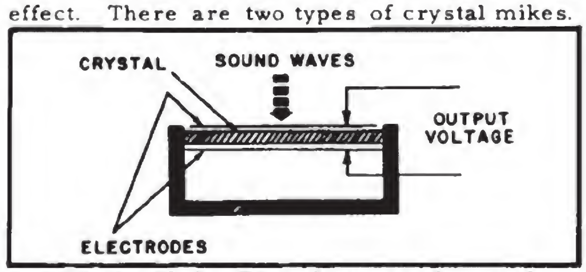

Figure 23-9 - Directly actuated crystal.

The directly actuated type, and the diaphragm actuated type, In the directly actuated type, the sound acts directly on the crystal.

In the directly actuated type shown in Figure 23-9, electrical contact is made to the crystal by the thin metal foil on each side of the crystal. When this type of crystal is activated directly by the pressure waves of the voice, the device is not efficient. When the sound waves strike its surface, the force is dissipated over the entire surface of the crystal. To obtain higher efficiency, a diaphragm is used. A diaphragm actuated type is shown in Figure 23-10. In this type, all of the force of the diaphragm is exerted on a small area of the crystal. Therefore, as the diaphragm moves back and forth, the voltage produced by the crystal varies at the same rate.

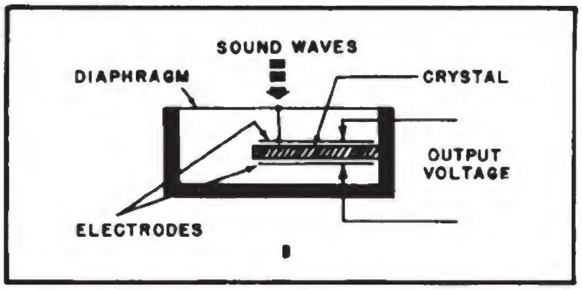

Figure 23-10 - Diaphragm actuated crystal microphone.

Since the diaphragm is mechanically connected to the crystal, there will be considerable stress placed on the crystal. The output of the diaphragm actuated type of crystal mike is higher than that of the directly actuated type.

The frequency response of the crystal mike in not very uniform. This is due to the inertia of the crystal. However, for applications such as amateur radio (or any non-critical application) they are widely used. Because of its high impedance, the crystal microphone may be directly connected to the input of the grid circuit of a speech amplifier. The output of the crystal microphone is in the order of about -55 db. The diaphragm type has a frequency response of 80 to 6, 000 cycles per second. The type of crystal most widely used is Rochelle salt because of its sensitivity. The disadvantages of the crystal microphone are its sensitivity to temperature and humidity changes, and it can be easily damaged by rough handling.

23-9. Dynamic Loudspeakers

There are basically two types of dynamic loudspeakers—the PERMANENT MAGNET DYNAMIC LOUDSPEAKER, and the ELECTROMAGNETIC DYNAMIC LOUDSPEAKER. The names of the devices imply the types of magnets used in the construction of the speakers. The operation of each type is the same. The function of the speaker is shown in the diagram in Figure 23-11.

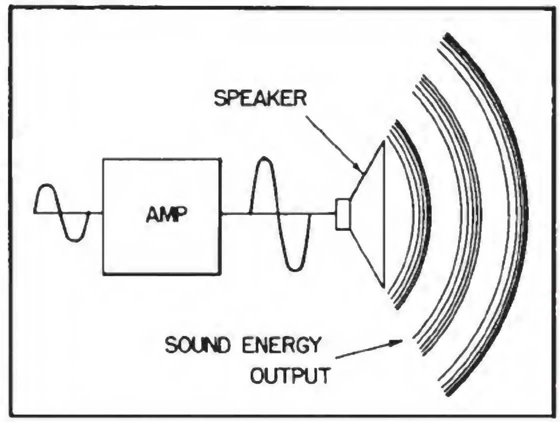

Figure 23-11 - Block diagram showing the function of a loudspeaker.

The purpose of a loudspeaker is to convert electrical energy into mechanical energy. The frequencies applied to the speaker are in the audio range. Therefore, a perfect speaker would be one that has a response embracing the entire audio range (from 20 to 20, 000 cycles per second).

The construction of the permanent magnet dynamic loudspeaker is shown in Figure 23-12.

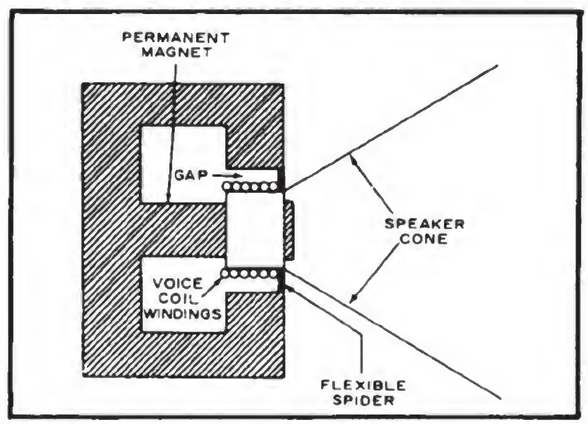

Figure 23-12 - Construction of permanent magnet dynamic loudspeaker.

In the diagram of Figure 23-12, the coil that is shown wrapped around the base of the cone of the loudspeaker is called a VOICE COIL. The audio frequency current output from the amplifier flows through it. The audio variations in passing through the voice coil will cause an alternating magnetic field to exist about the voice coil. Since the voice coil is located between the poles of the permanent magnet, the magnetic field alternations about the voice coil

A7. The velocity mike has better response, but less of an output.

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will interact with the stationary field established by the permanent magnet. The voice coil is wound around a bakelite core, and has the ability to move back and forth. Since the voice coil is physically connected to the paper cone, any movement of the voice coil will cause a corresponding movement of the cone. Because the paper cone has a large diameter, it will possess a large surface area. Any movement by it will displace a large volume of air causing sound. Any audio current variations will cause a displacement of the voice coil due to the interaction of the magnetic fields. The moving voice coil will cause the paper cone to move resulting in an audible sound. The higher the value of current, the louder the sound will be. The paper cone and voice coil are suspended from a metal frame by a flexible device called a SPIDER. The spider insures that the voice coil remains centered around the permanent magnet but allows back and forth movement of the voice coil and cone. It also returns the coil to its original position when no current is flowing through the coil.

A voice coil is a low impedance device, and is usually connected to the output of a power amplifier that has a high output impedance. An impedance matching transformer is used to match the output impedance of the amplifier to the input impedance of the speaker. The connection of the loudspeaker to the amplifier is shown in Figure 23-13.

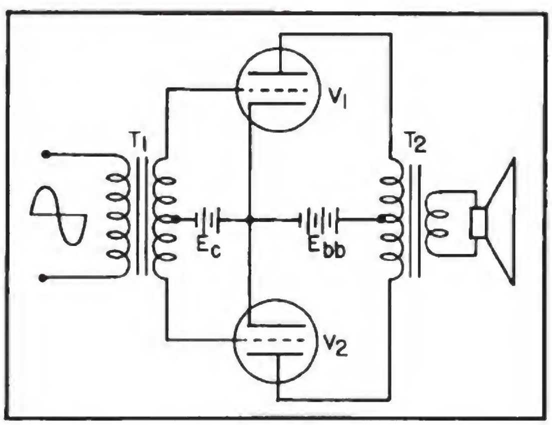

Figure 23-13 - Speaker-amplifier connections.

The movement of the voice coil and the paper cone is dependent upon the strength of the magnetic field about the voice coil and the strength of the fixed magnetic field. The strength of the magnetic field produced by the voice coil is a function of the magnitude of the current flow through it. The strength of the field around the permanent magnet is determined by the size of the magnet and its composition. The permanent magnet may be quite large, and is a rough measure of the quality of the speaker. The heavier the magnet is, the higher the quality of reproduction.

The advantages of the permanent magnet type of speaker are its light weight, and the fact that it does not need an external source of power. It is used predominately in communications and high-fidelity applications. The permanent magnet type is usually rated at between 2 and 30 watts. The impedance range is from 3 to 16 ohms. The weight of the speakers can range from a few ounces to many pounds, but the outside diameter very seldom is greater than 16 inches. In many applications, the prescribed output transformer is mounted directly on the magnet housing.

The permanent magnets used for these speakers are made of various combinations of ferro-magnetic materials. Alloys are employed in construction so that the magnet will retain its magnetization long after the magnetizing force has been removed. The common metals used in construction are aluminum, nickel, cobalt, steel, and lead. The proportions in which these metals are used governs the magnetizing ability of the magnet. One of the more popular compositions is ALNICO which is made of aluminum, nickel, and cobalt.

The other type of speaker, the electromagnetic type, will not be given detailed consideration because it is infrequently used. The only difference between it and the permanent magnet type is that an electromagnet replaces the permanent magnet in the housing. A steady value of dc current must be provided to sustain the magnetic field for the electromagnet. This is usually done by using the FIELD COIL in the speaker as the filter choke for the power supply A diagram of the electromagnetic type is shown in Figure 23-14.

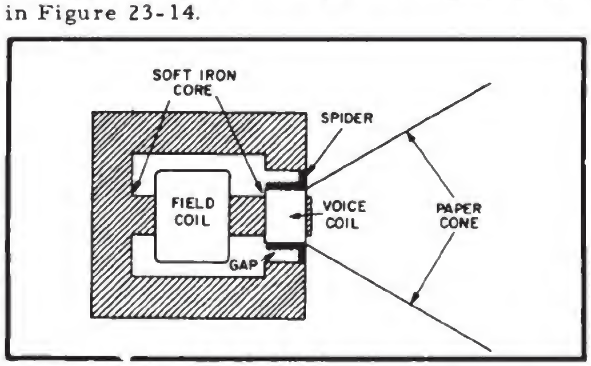

Figure 23-14 - Electromagnetic type of speaker.

The electromagnetic type of speaker also

possesses a low value of input impedance, and requires an impedance matching transformer when its input is connected to the output of a high impedance output amplifier.

Although the permanent magnet type of speaker is more expensive than the electro-magnetic type, the permanent magnet is more frequently used because it does not require a dc supply voltage. If an electromagnetic speaker is to be located at a great distance from the supply of dc voltage and the output of the amplifier, the losses in the line are considerable. The electromagnetic type is rapidly disappearing because of the perfected permanent magnets that are now being developed.

EXERCISE 23

1. Describe the terms "quiet" and "loud".
2. Why is it said that the human ear is a logarithmic device?
3. What is the purpose of the decibel unit?
4. Define a decibel.
5. How many decibels correspond to a power ratio of 150?
6. If an amplifier has a 45 db gain, what voltage ratio does this gain represent? Assume equal resistances.
7. What is the purpose of a reference level?
8. What is meant by the term "dbm"?
9. What is the purpose of a VU meter?
10. What is meant by the term "high fidelity"?
11. Describe the function of a microphone.
12. Of what is sound composed?
13. What is a harmonic?
14. What is pitch?
15. Are microphones efficient devices?
16. What is frequency response? How does the term apply to a microphone?
17. Define sensitivity.
18. Compare the impedances of the carbon mike and the crystal mike.
19. What is the assumed power level for microphones?
20. Describe the operation of the carbon microphone.
21. Compare the characteristics of all of the microphones contained in this chapter.
22. What is the purpose of impedance matching?
23. What is the function of a loudspeaker?
24. Describe the operation of the permanent magnet type of speaker.
25. Compare the permanent magnet type of speaker to the electromagnetic type.

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